Sterile neutrinos for believers and non-believers

Georgia Karagiorgi, Columbia U.

FNAL Theoretical Physics Seminar
June 27, 2013

Outline

1. Evidence for and shortcomings of (<u>light</u>) sterile neutrino oscillations

Experimental hints for "short baseline" neutrino oscillations
$\nu_\mu \rightarrow \nu_e$ and $\nu_e \rightarrow \nu_{\cancel{e}}$

Lack of signals in $\nu_\mu \rightarrow \nu_{\cancel{\mu}}$,
Simplest models are insufficient

Cosmological constraints

2. Future phenomenological tests of sterile neutrino models

No sterile neutrinos in “Standard Model*”

**Minimally* extended to account for neutrino mass

Three-Neutrino Oscillation Parameters

3 "flavor" states
3 "mass" states

weak ("flavor") states | "mass" states

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3}e^{i\delta} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

3×3 unitary mixing matrix U

Three-Neutrino Oscillation Parameters

1. **Why 3 "flavor" states?**
2. **Why 3 "mass" states?**

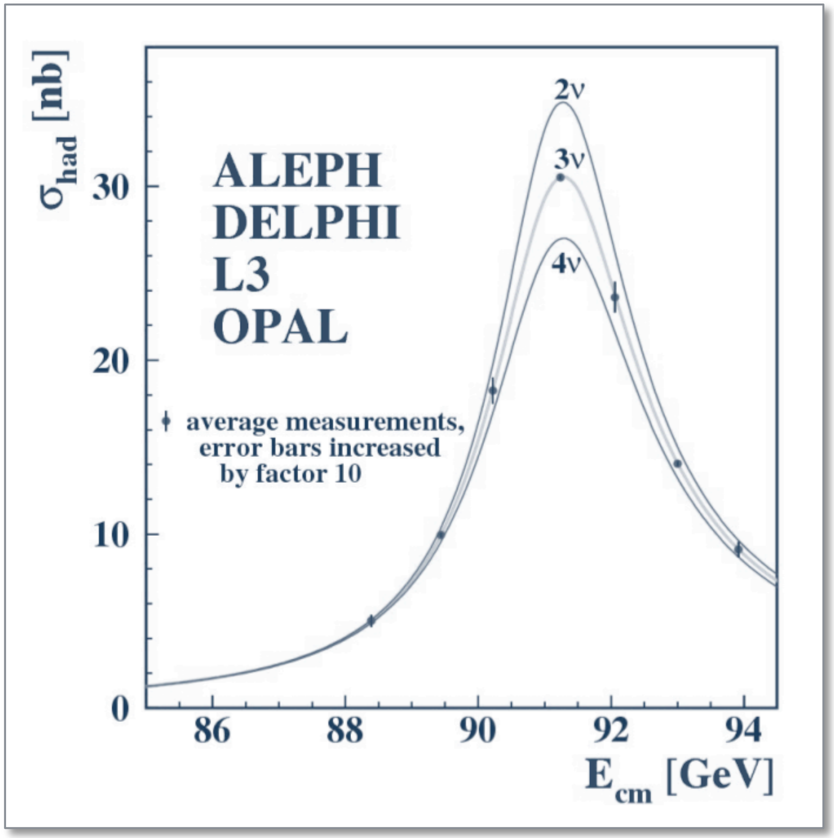
weak ("flavor") states — "mass" states

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3}e^{i\delta} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

3×3 unitary mixing matrix U

Three-Neutrino Oscillation Parameters

1. Why 3 "flavor" states?



$$N_\nu = \frac{\Gamma_{\text{inv}}}{\Gamma_\ell}\left(\frac{\Gamma_\ell}{\Gamma_\nu}\right)_{\text{SM}}$$

$$= 2.984 \pm 0.008$$

[Phys. Reports 427, 257 (2006)]

Measurement of the invisible Z width: $Z \rightarrow \nu\bar{\nu}$

Three-Neutrino Oscillation Parameters

2. Why 3 "mass" states?

1. Theoretical prejudice
2. Limits on number of light neutrino species from cosmology

Model	Data	N_{eff}
N_{eff}	W-5+BAO+SN+H_0	$4.13^{+0.87(+1.76)}_{-0.85(-1.63)}$
	W-5+LRG+H_0	$4.16^{+0.76(+1.60)}_{-0.77(-1.43)}$
	W-5+CMB+BAO+XLF+f_{gas}+H_0	$3.4^{+0.6}_{-0.5}$
	W-5+LRG+maxBCG+H_0	$3.77^{+0.67(+1.37)}_{-0.67(-1.24)}$
	W-7+BAO+H_0	$4.34^{+0.86}_{-0.88}$
	W-7+LRG+H_0	$4.25^{+0.76}_{-0.80}$
	W-7+ACT	5.3 ± 1.3
	W-7+ACT+BAO+H_0	4.56 ± 0.75
	W-7+SPT	3.85 ± 0.62
	W-7+SPT+BAO+H_0	3.85 ± 0.42
	W-7+ACT+SPT+LRG+H_0	$4.08^{(+0.71)}_{(-0.68)}$
	W-7+ACT+SPT+BAO+H_0	3.89 ± 0.41
$N_{eff}+f_\nu$	W-7+CMB+BAO+H_0	$4.47^{(+1.82)}_{(-1.74)}$
	W-7+CMB+LRG+H_0	$4.87^{(+1.86)}_{(-1.75)}$
$N_{eff}+\Omega_k$	W-7+BAO+H_0	4.61 ± 0.96
	W-7+ACT+SPT+BAO+H_0	4.03 ± 0.45
$N_{eff}+\Omega_k+f_\nu$	W-7+ACT+SPT+BAO+H_0	4.00 ± 0.43
$N_{eff}+f_\nu+w$	W-7+CMB+BAO+H_0	$3.68^{(+1.90)}_{(-1.84)}$
	W-7+CMB+LRG+H_0	$4.87^{(+2.02)}_{(-2.02)}$
$N_{eff}+\Omega_k+f_\nu+w$	W-7+CMB+BAO+SN+H_0	$4.2^{+1.10(+2.00)}_{-0.61(-1.14)}$
	W-7+CMB+LRG+SN+H_0	$4.3^{+1.40(+2.30)}_{-0.54(-1.09)}$

[pre-Planck data: arXiv:1204.5379]

Three-Neutrino Oscillation Parameters

Mixing matrix parameterization for two-mass-scale dominance scenario:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3}e^{i\delta} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

three mixing angles:

$$U = \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \times \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}$$

"solar" $\theta_{12} \approx 34°$

"reactor" $\theta_{13} = 9°$

"atmospheric" $\theta_{23} \approx 45°$

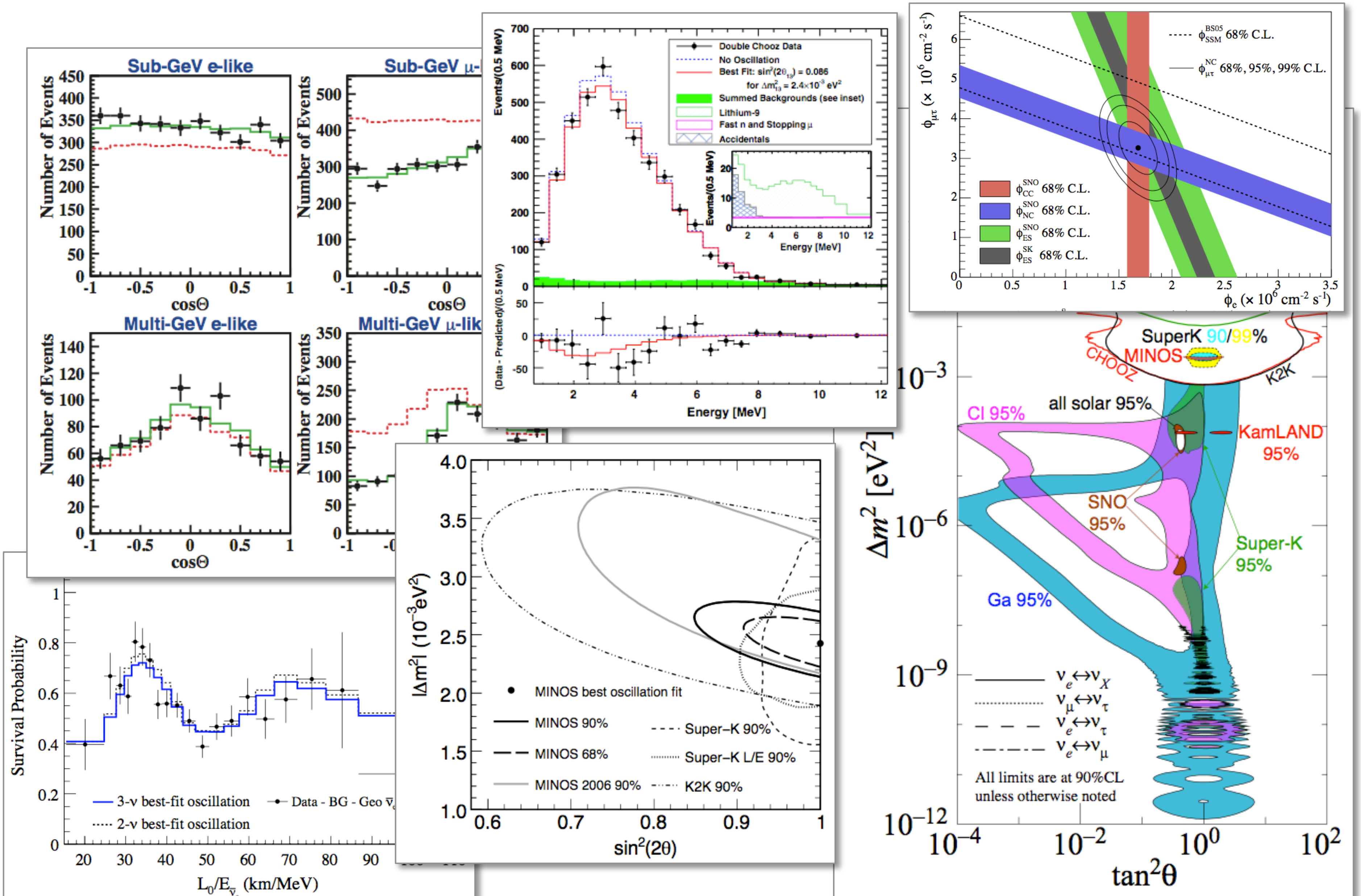
a CP-violating phase:

If $\delta \neq 0$, then have CP violation $\Rightarrow P(\nu_\mu \to \nu_e) \neq P(\bar{\nu}_\mu \to \bar{\nu}_e)$

and three mass parameters:

$m_1, m_2, m_3 \rightarrow$ two independent Δm^2

Evidence for three-neutrino picture



Three-Neutrino Oscillation Parameters

Mixing matrix parameterization for two-mass-scale dominance scenario:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3}e^{i\delta} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

As of 2012, the only unknown parameter!

three mixing angles:

$$U = \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \times \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}$$

"solar" $\theta_{12} \approx 34°$

"reactor" $\theta_{13}=9°$

"atmospheric" $\theta_{23} \approx 45°$

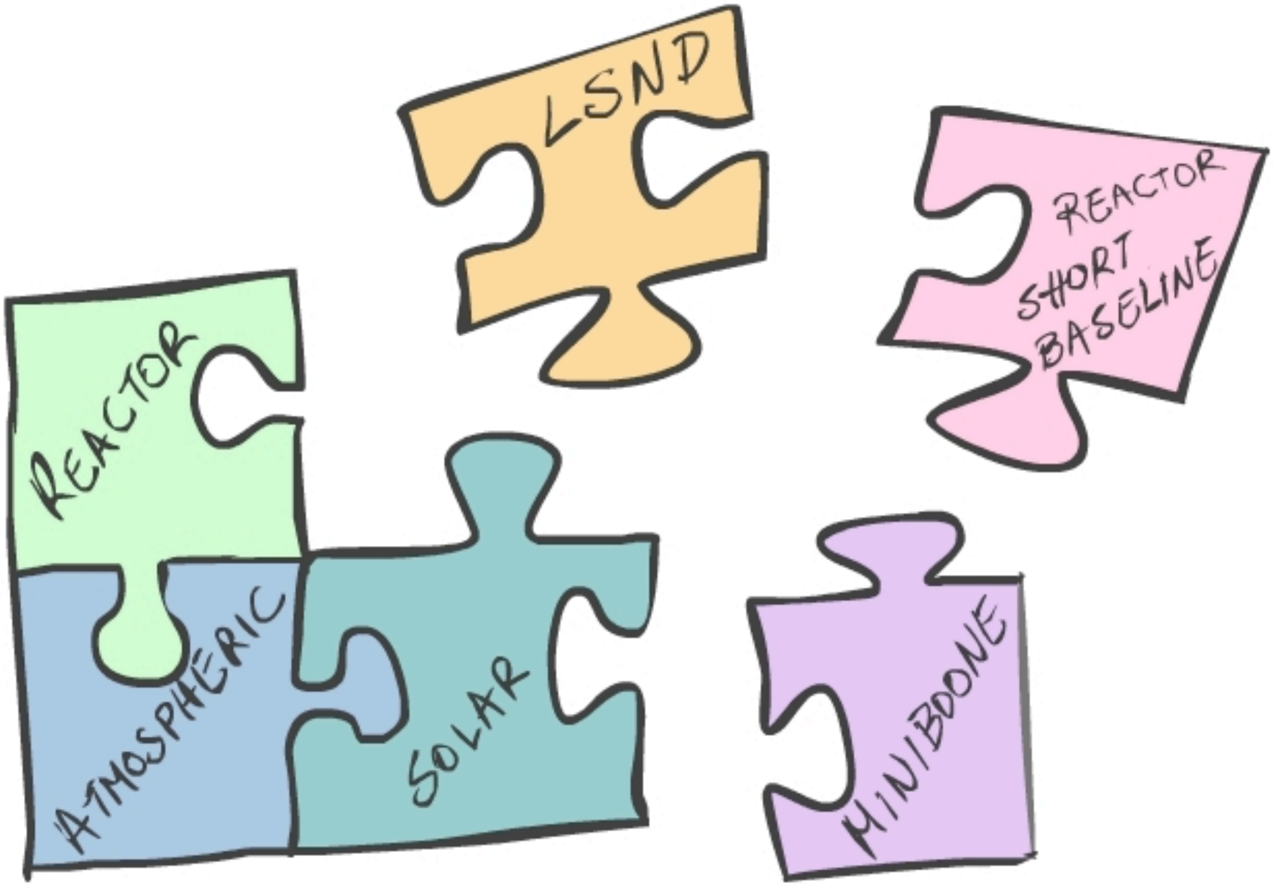
a CP-violating phase:

If $\delta \neq 0$, then have CP violation $\Rightarrow \; P(\nu_\mu \to \nu_e) \neq P(\bar{\nu}_\mu \to \bar{\nu}_e)$

and three mass parameters:

$m_1, m_2, m_3 \rightarrow$ two independent Δm^2

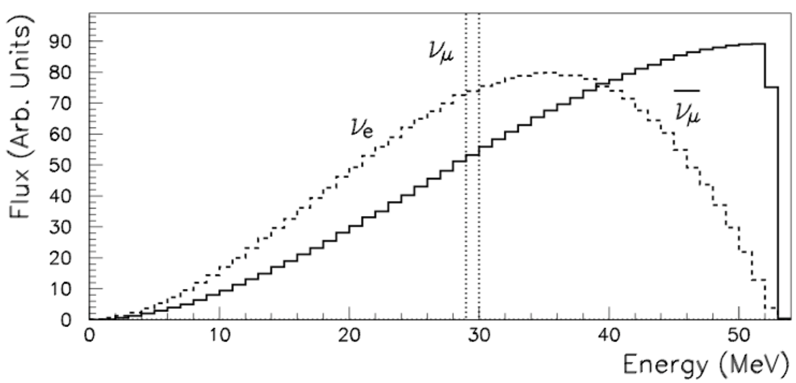
Why, or, why not sterile neutrinos?

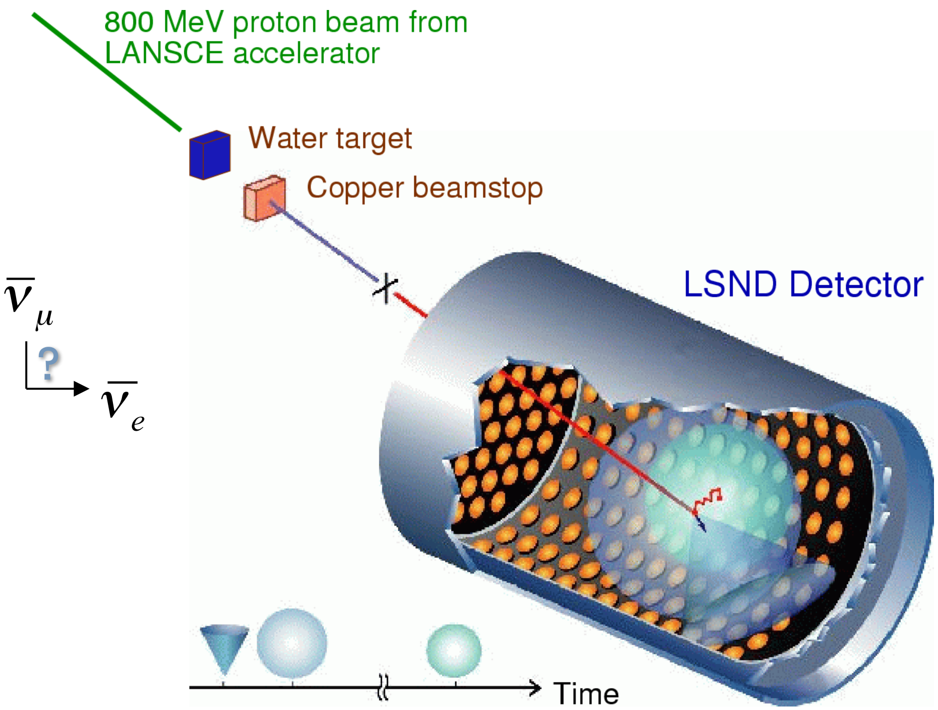


Puzzle piece #1: LSND Experiment

μ^+ decay-at-rest experiment:

$$\pi^+ \rightarrow \mu^+ \nu_\mu$$
$$\hookrightarrow e^+ \nu_e \bar{\nu}_\mu$$
$$\overset{?}{\hookrightarrow} \bar{\nu}_e$$





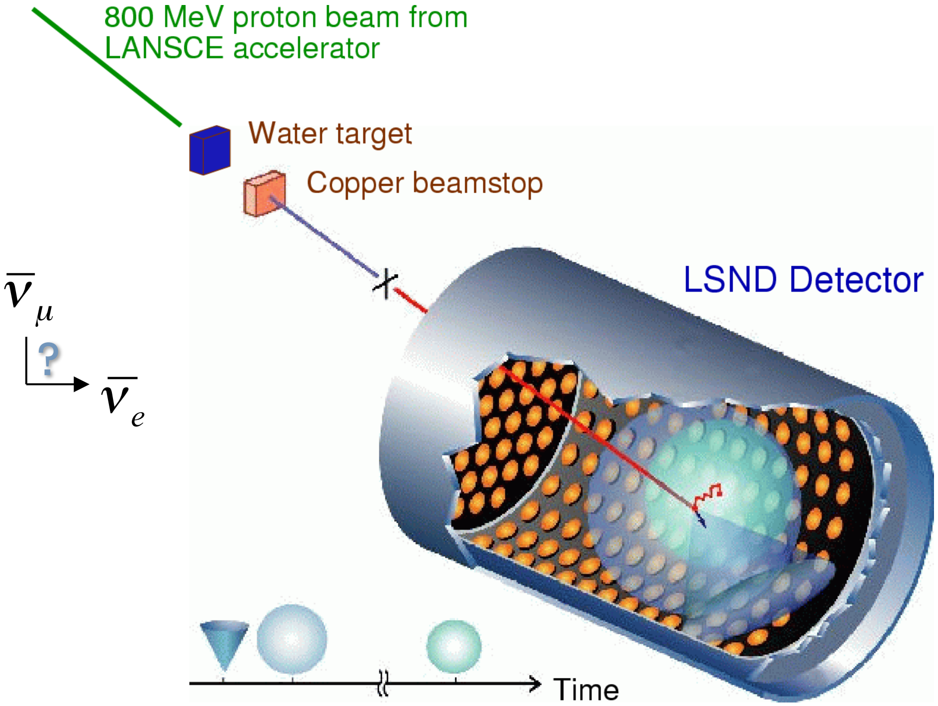
Well-predicted neutrino flux and cross-section.
Very low $\bar{\nu}_e$ backgrounds.

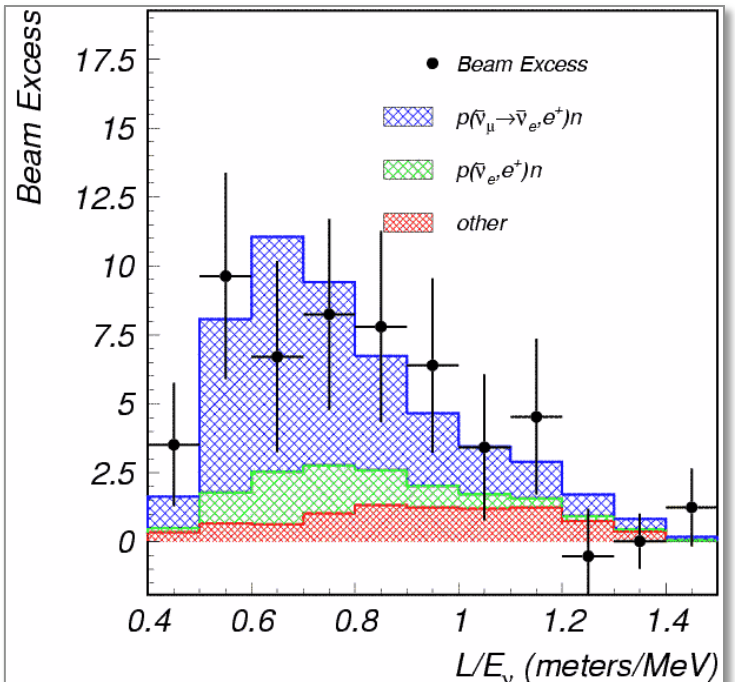
$\bar{\nu}_e$ detection via inverse-beta-decay: $\bar{\nu}_e + p \rightarrow e^+ + n$
(coincidence signal)

Puzzle piece #1: LSND Experiment

μ^+ decay-at-rest experiment:

$$\pi^+ \to \mu^+ \nu_\mu$$
$$\hookrightarrow e^+ \nu_e \bar{\nu}_\mu$$
$$\overset{?}{\hookrightarrow} \bar{\nu}_e$$



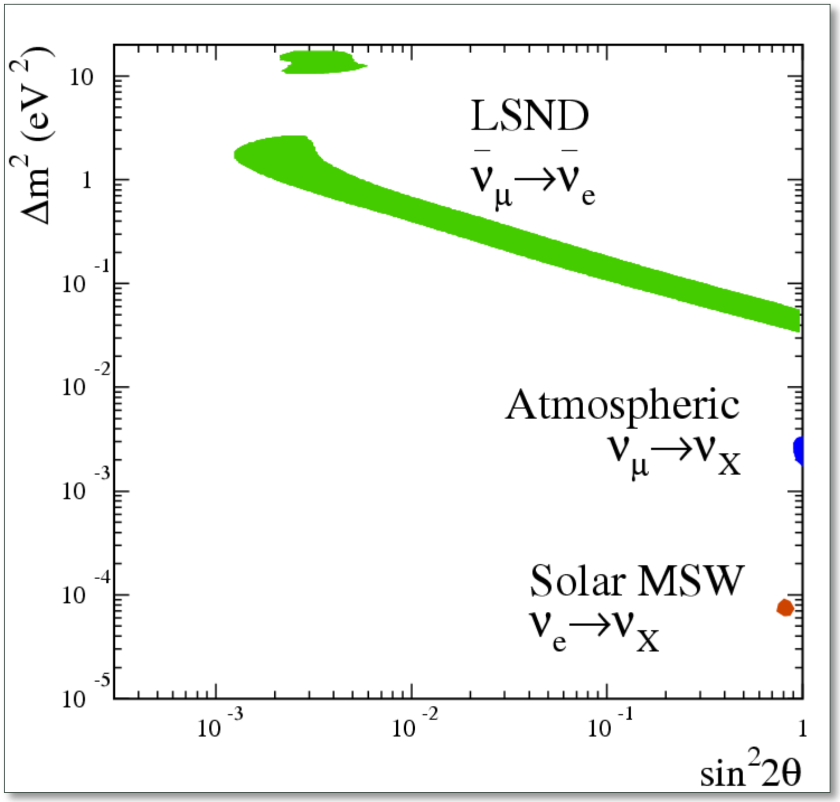


Observed excess of $\bar{\nu}_e$ described by oscillation probability:
$P(\bar{\nu}_\mu \to \bar{\nu}_e) = (0.264 \pm 0.067 \pm 0.045)\ \%$

(3.8σ evidence)

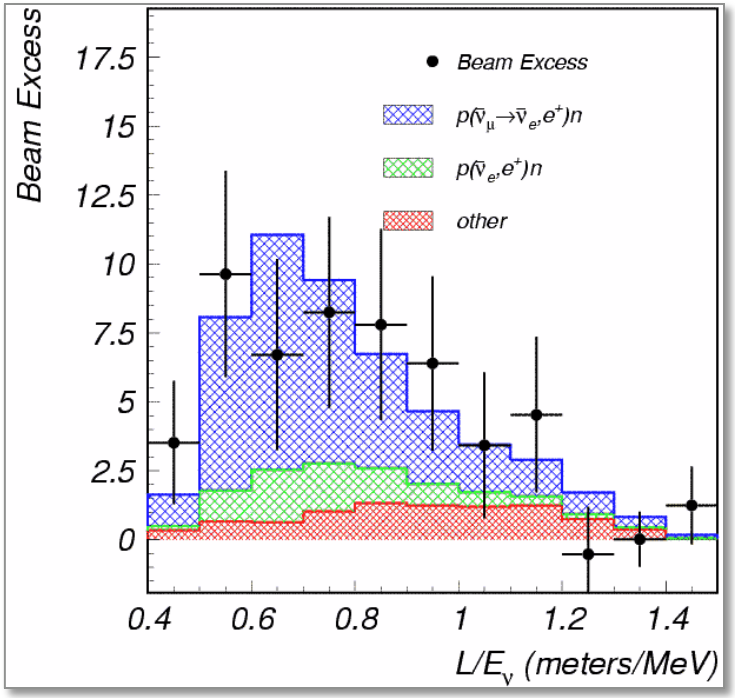
[C. Athanassopoulos et al., Phys. Rev. Lett. 75, 2650 (1995); 81,1774(1998); A.Aguilaretal., Phys. Rev. D64, 112007(2001).]

Puzzle piece #1: LSND Experiment



Points to large Δm^2
if interpreted as
two-neutrino oscillations:

$$P(\nu_\mu \to \nu_e) = \sin^2 2\vartheta_{\mu e} \sin^2(1.27\Delta m^2 L/E)$$



Observed excess of $\bar{\nu}_e$
described oscillation probability:
$P(\bar{\nu}_\mu \to \bar{\nu}_e) = (0.264 \pm 0.067 \pm 0.045)\ \%$

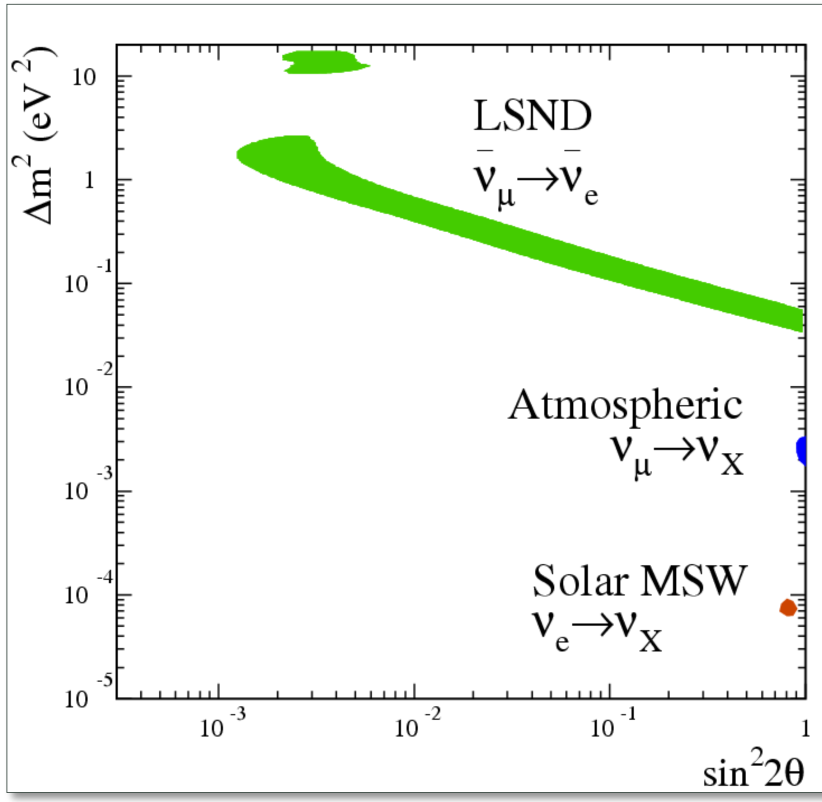
(3.8σ evidence)

[C. Athanassopoulos et al., Phys. Rev. Lett. 75, 2650 (1995); 81,1774(1998); A.Aguilaretal., Phys. Rev. D64, 112007(2001).]

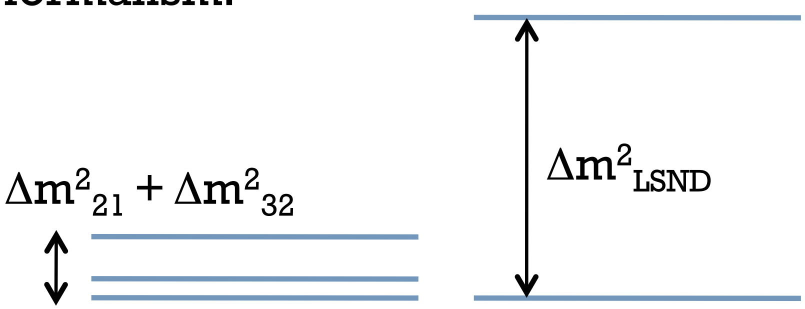
Puzzle piece #1: LSND Experiment

Points to large Δm^2
if interpreted as
two-neutrino oscillations:

$$P(\nu_\mu \to \nu_e) = \sin^2 2\vartheta_{\mu e} \sin^2(1.27\Delta m^2 L/E)$$



In conflict with three-neutrino formalism!



$\Delta m^2_{LSND} >> \Delta m^2_{21} + \Delta m^2_{32}$

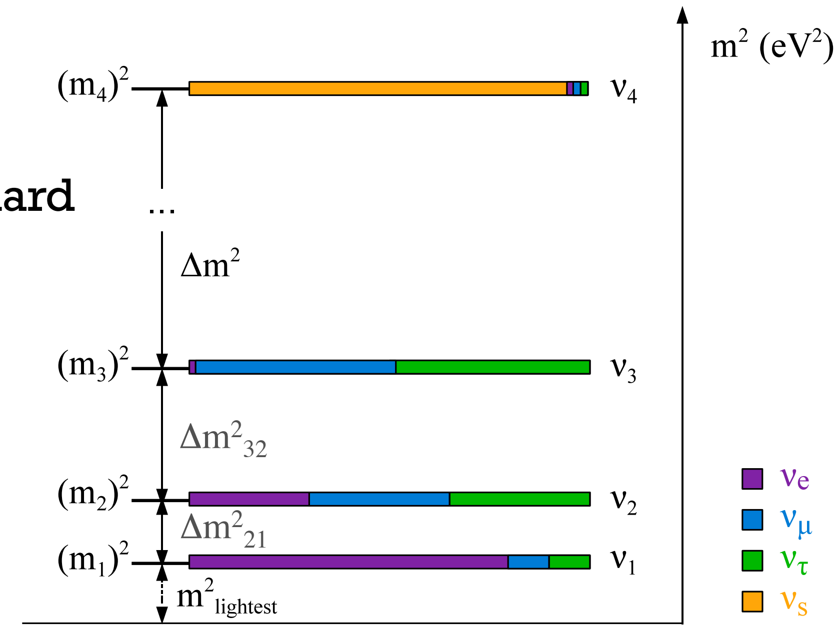
Needs more than 3 neutrino mass states!

Possible interpretation: sterile neutrino

Additional neutrino "flavor" (and mass) state which has **no weak interactions** (through the standard W/Z bosons)

Additional mass state is assumed to be produced through mixing with the standard model neutrinos

→ Can affect neutrino oscillations through mixing



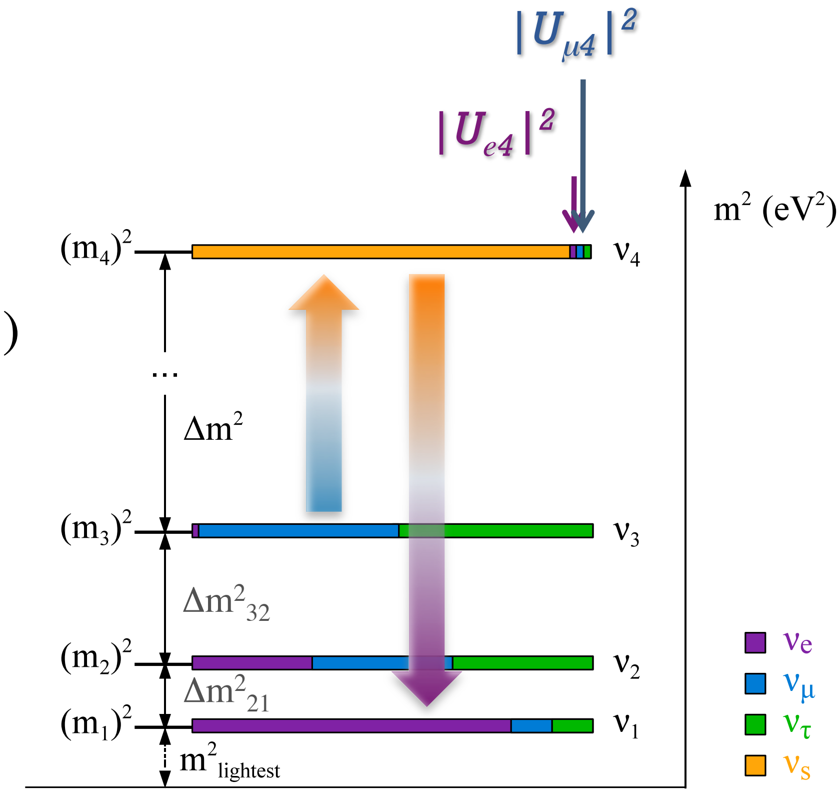
Sterile Neutrino Oscillation Formalism

Oscillation effects:

$\nu_\mu \rightarrow \nu_e$ appearance*:

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\vartheta_{\mu e} \sin^2(1.27\Delta m^2 L/E)$$

$$\sin^2 2\vartheta_{\mu e} \rightarrow 4|U_{e4}|^2|U_{\mu 4}|^2$$



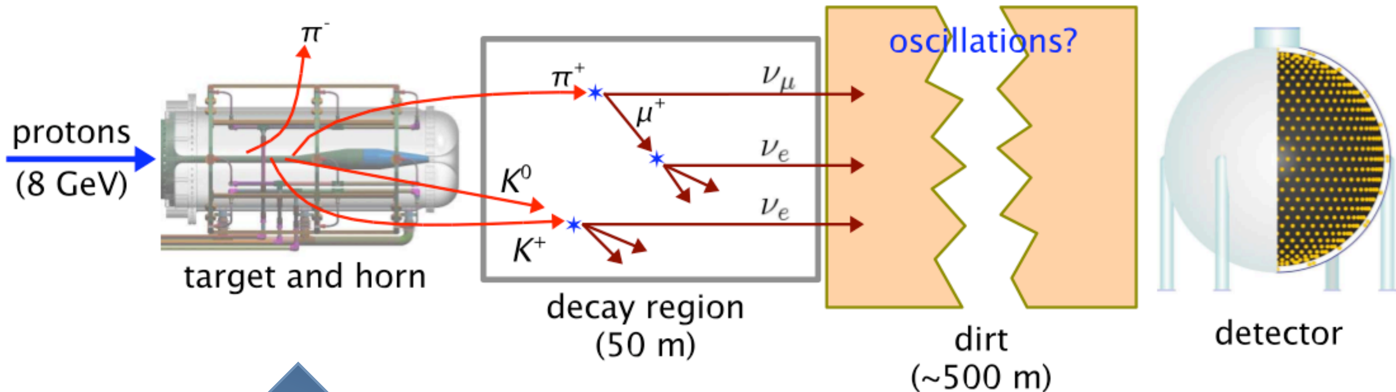
Explains LSND result

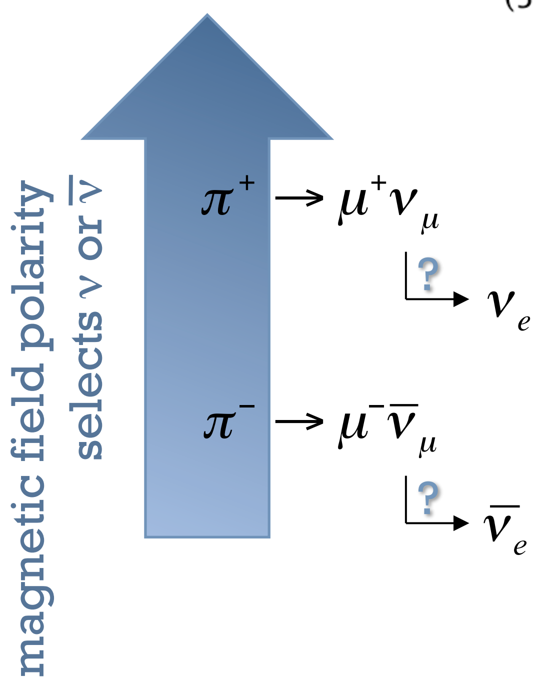
(3+1)

*Approximation: $m_1, m_2, m_3 << m_4 \rightarrow$ $m_1, m_2, m_3 = 0$

Puzzle piece #2: MiniBooNE

MiniBooNE was proposed to independently test the LSND oscillation hypothesis:





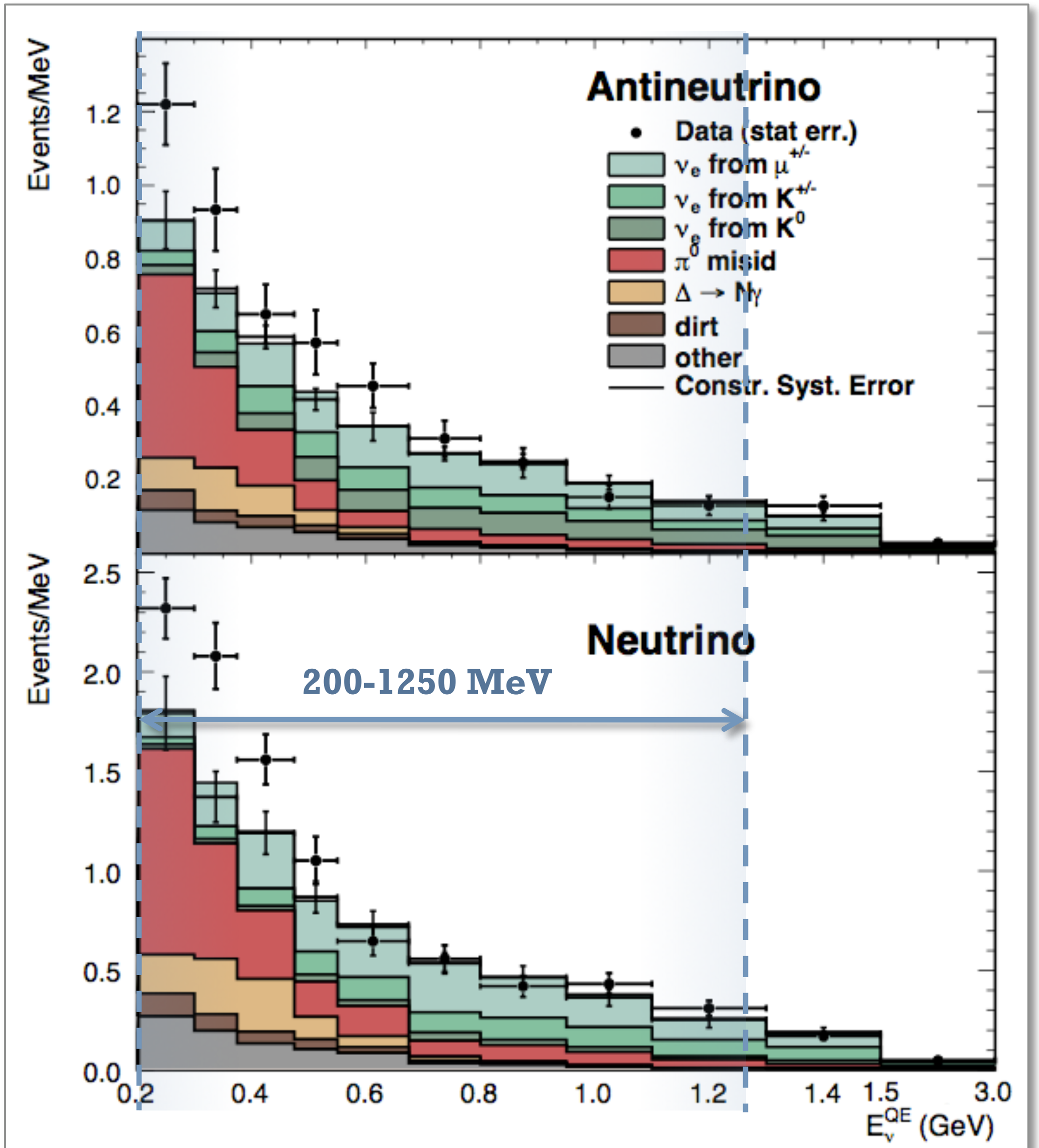
Similar L/E as LSND

but

- Different energy, beam and detector systematics

- Different event signatures and backgrounds (cherenkov detector)

Puzzle piece #2: MiniBooNE



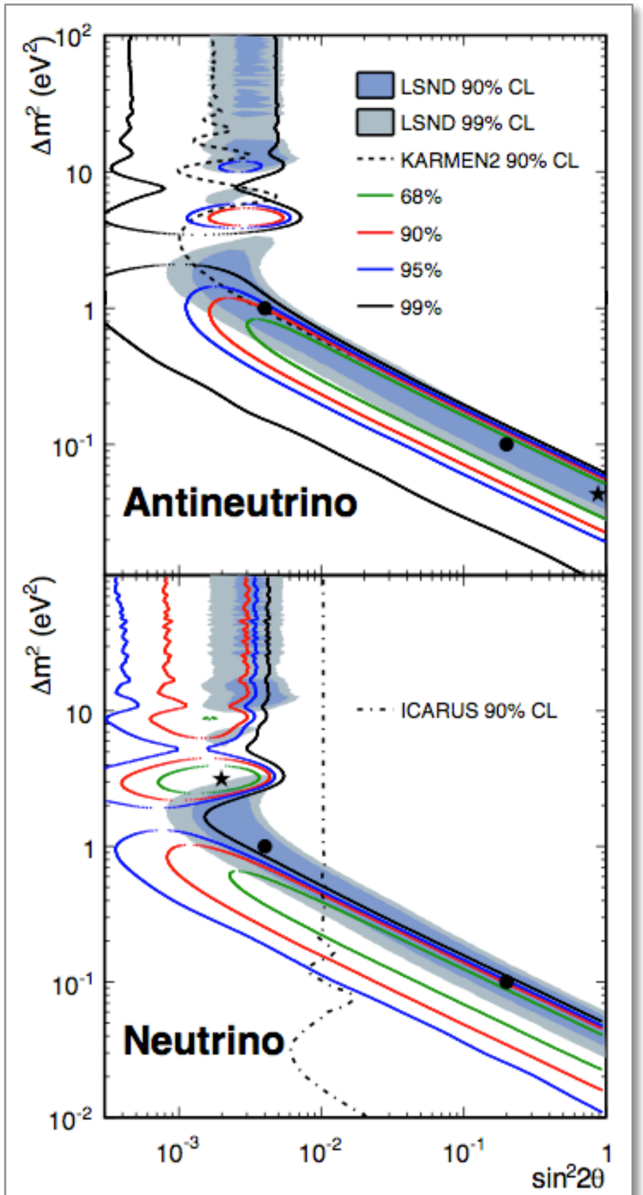
[arXiv:1303.2588, submitted to Phys. Rev. Let.; see also:
Phys.Rev.Lett.110.161801,2012
Phys.Rev.Lett.98.231801,2007,
Phys.Rev.Lett.102.101802,2009,
Phys.Rev.Lett.103:111801,2009,
Phys.Rev.Lett.105:181801,2010]

Oscillation signal region:
200-1250 MeV

Antineutrino search:
2.8σ excess
Excess of events is at both high and "low energy."

Neutrino search:
3.4σ excess
Excess of events is at "low energy," E < 475 MeV.

Puzzle piece #2: MiniBooNE



[arXiv:1303.2588, submitted to Phys. Rev. Let.; see also: Phys.Rev.Lett.110.161801,2012 Phys.Rev.Lett.98.231801,2007, Phys.Rev.Lett.102.101802,2009, Phys.Rev.Lett.103:111801,2009, Phys.Rev.Lett.105:181801,2010]

Antineutrino (3+1) best fit:
χ^2-probability = 66%
$(\Delta m^2, \sin^2 2\theta) = (0.04\ \mathrm{eV}^2, 0.88)$

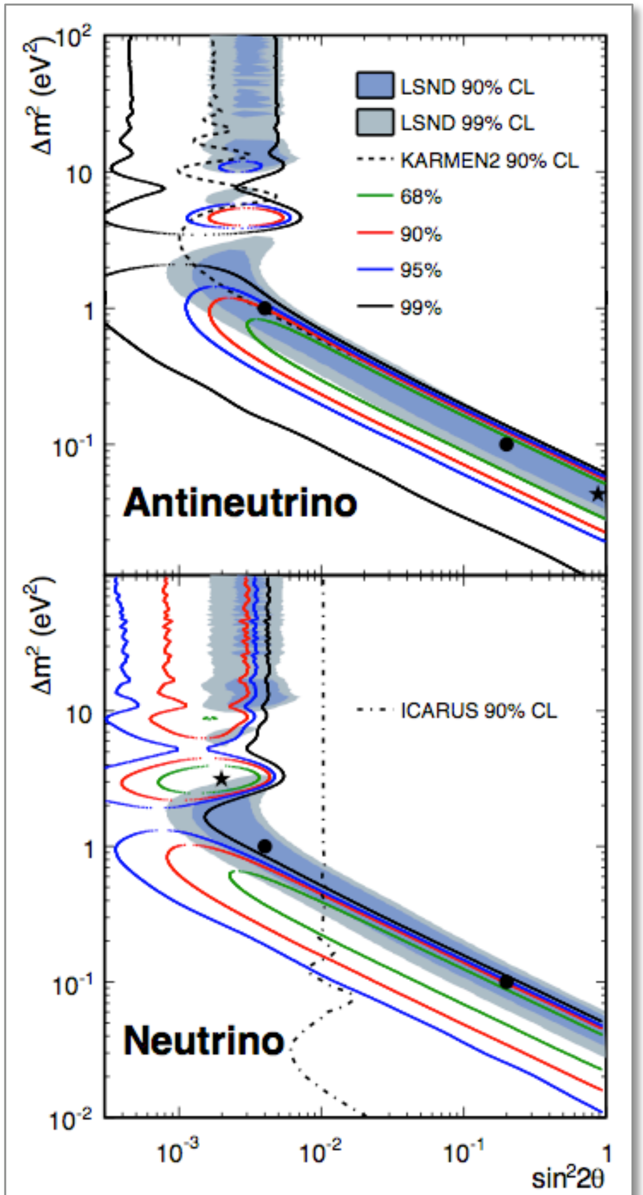
Background-only relative to best fit: 0.5%

Neutrino (3+1) best fit:
χ^2-probability = 6.1%
$(\Delta m^2, \sin^2 2\theta) = (3.14\ \mathrm{eV}^2, 0.002)$

Background-only relative to best fit: 2%

Both are consistent with (3+1) oscillations in general, but MiniBooNE antineutrino allowed parameters are in better agreement with LSND parameters.

Puzzle piece #2: MiniBooNE



Barring CP violation,

$$P(\nu_\mu \rightarrow \nu_e) \equiv P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$$

(3+1) approximation
does not allow for CP violation

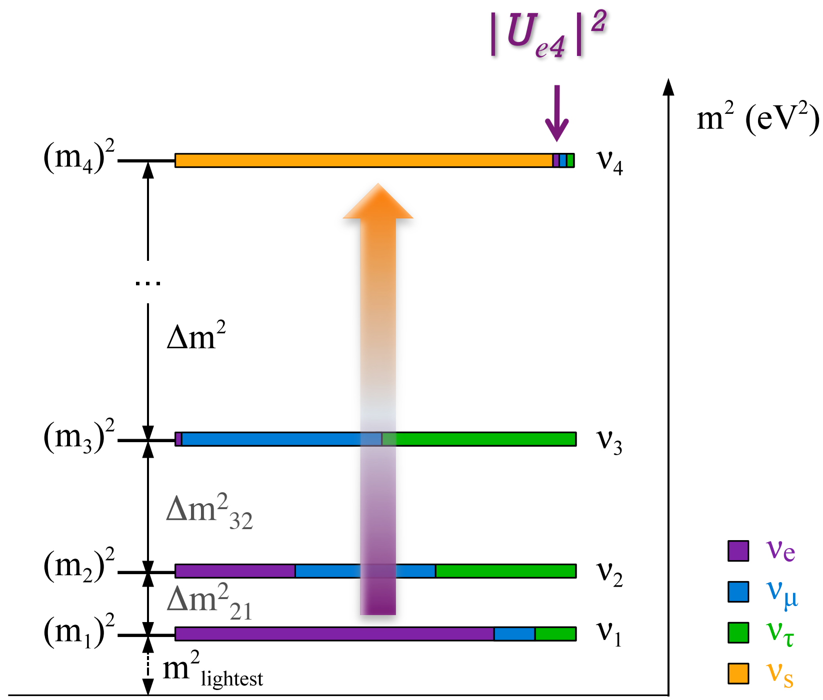
Sterile Neutrino Oscillation Formalism

$\nu_\mu \rightarrow \nu_e$ appearance implies ν_μ and ν_e disappearance!

ν_e disappearance*:

$$P(\nu_e \rightarrow \nu_e) = 1 - \sin^2 2\vartheta_{ee} \sin^2(1.27\Delta m^2 L/E)$$

$$\sin^2 2\vartheta_{ee} \rightarrow 4|U_{e4}|^2\left(1-|U_{e4}|^2\right)$$



(3+1)

*Approximation: $m_1, m_2, m_3 << m_4 \rightarrow \quad m_1, m_2, m_3 = 0$

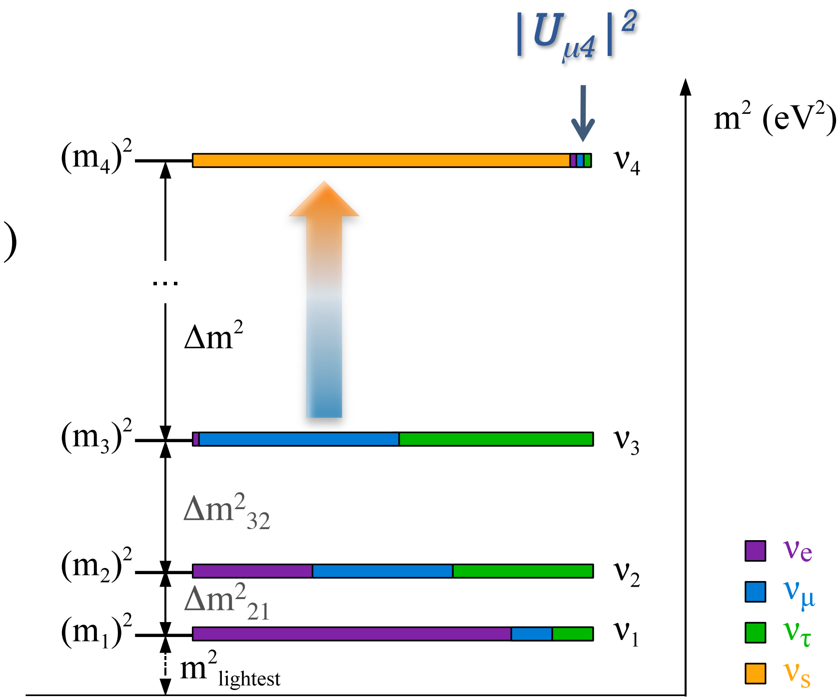
Sterile Neutrino Oscillation Formalism

$\nu_\mu \rightarrow \nu_e$ appearance implies ν_μ and ν_e disappearance!

ν_μ disappearance*:

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2 2\vartheta_{\mu\mu} \sin^2(1.27\Delta m^2 L/E)$$

$$\sin^2 2\vartheta_{\mu\mu} = 4|U_{\mu 4}|^2\left(1-|U_{\mu 4}|^2\right)$$

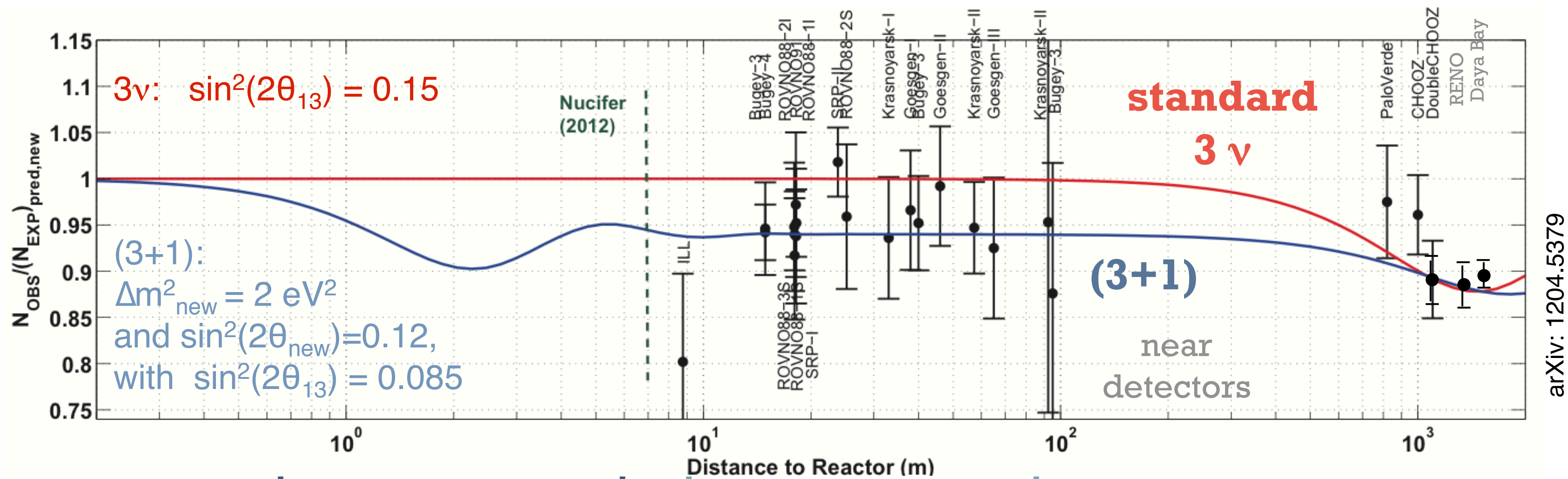


(3+1)

*Approximation: $m_1, m_2, m_3 << m_4 \rightarrow \quad m_1, m_2, m_3 = 0$

Puzzle piece #3: Reactor Anomaly

$\bar{\nu}_e \rightarrow \bar{\nu}_s$ disappearance?



region to explore for sterile neutrinos

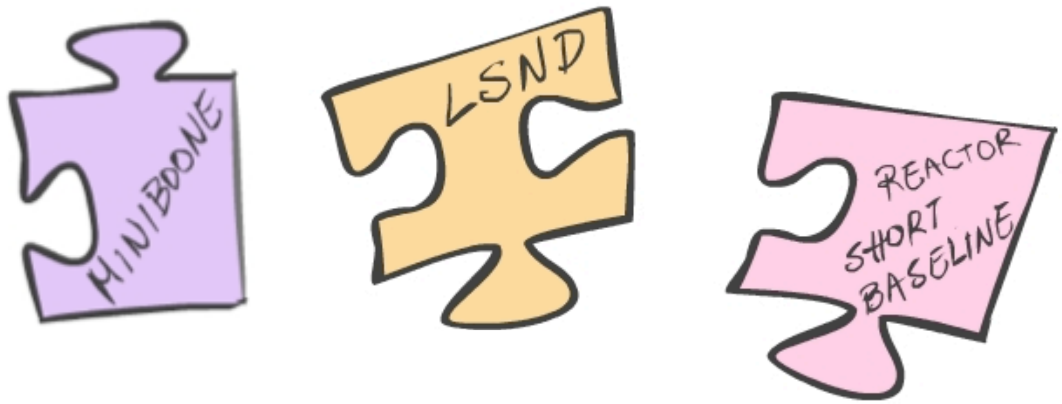
older reactor exps at close distances
$R = 0.927 \pm 0.023$ (3.0σ)
1.4σ when θ_{13} included
[arXiv:1303.0900]

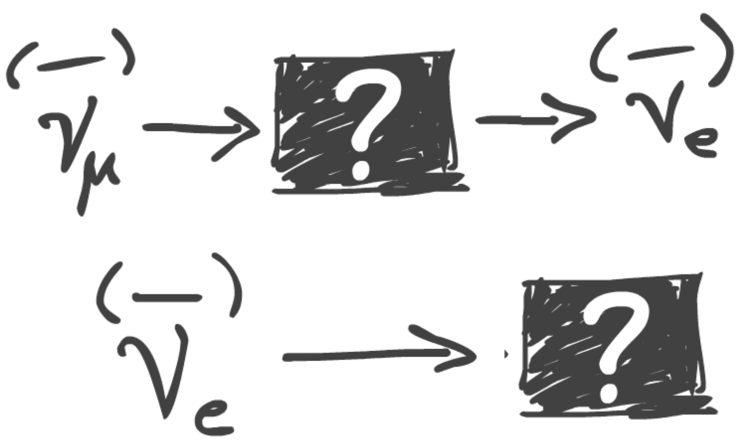
current reactor experiments

Fewer reactor neutrinos than expected at short baselines

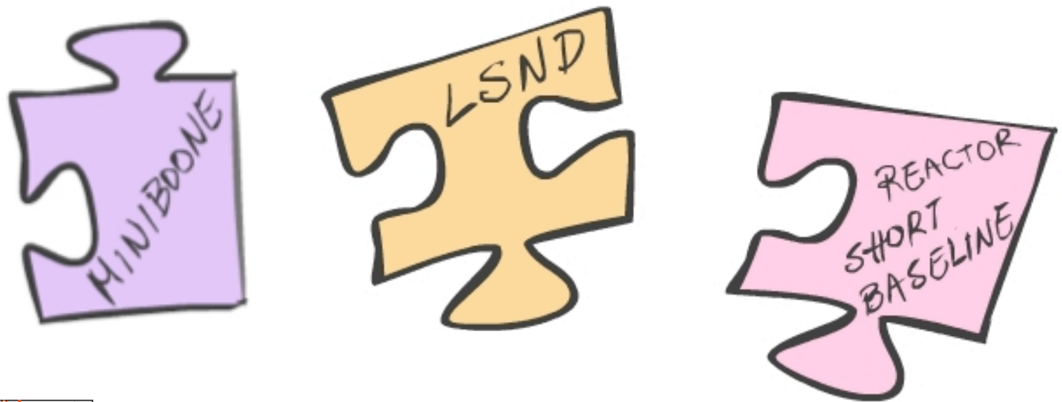
→ **A possible interpretation: sterile neutrino osc. with $\Delta m^2 \sim 1\,\text{eV}^2$ and $\sin^2 2\theta \sim 0.1$**

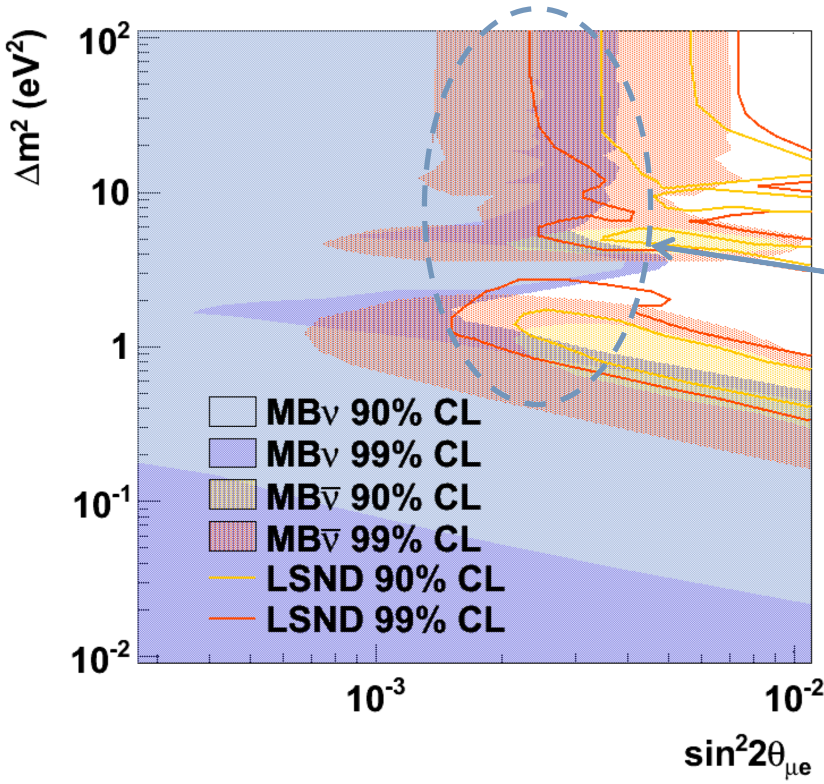
1. Can all three signatures be explained by (3+1) sterile neutrino hypothesis?





1. Can all three signatures be explained by (3+1) sterile neutrino hypothesis?

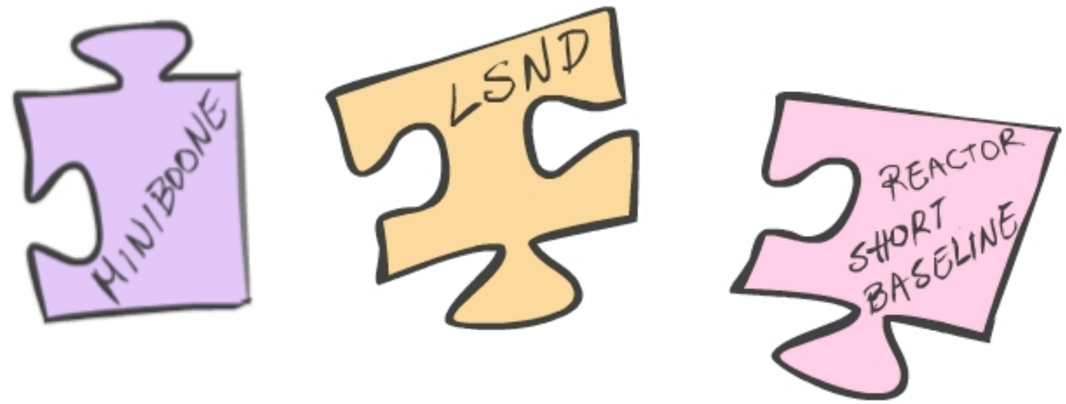




Reactor short-baseline consistent with these values

A: *Yes!*

1. Can all three signatures be explained by (3+1) sterile neutrino hypothesis?

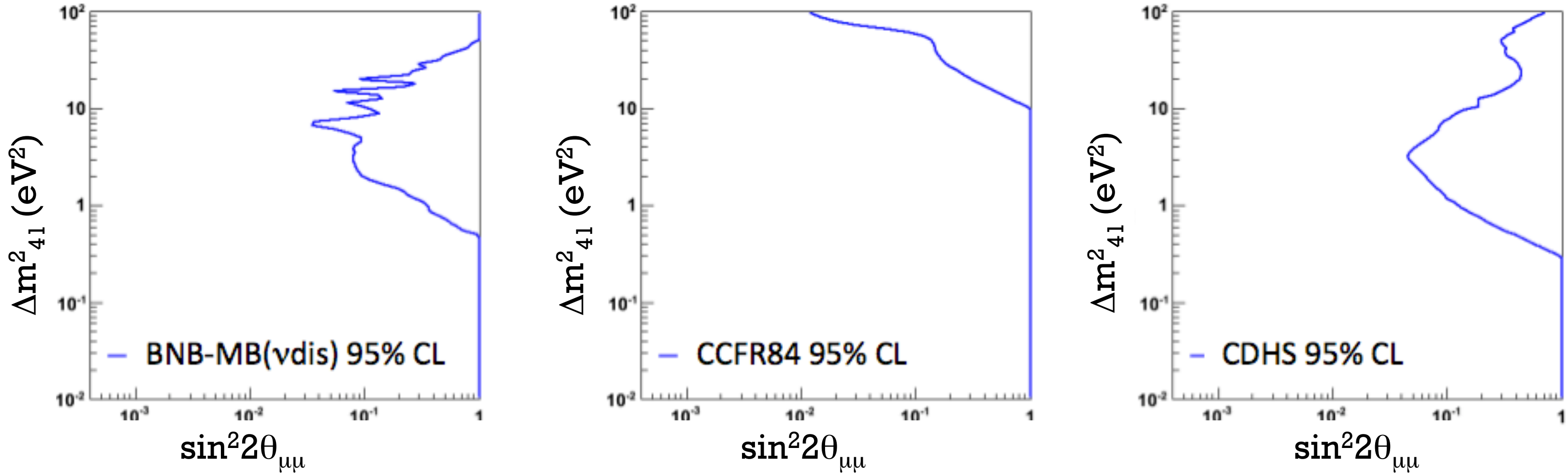


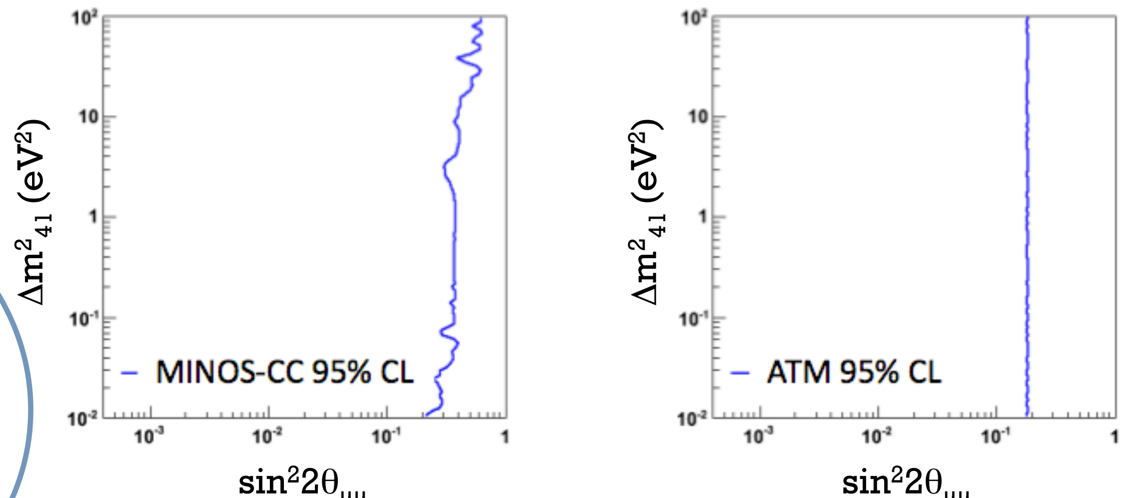
2. What about information from other experiments sensitive to high-Δm^2 oscillations?

$\overset{(-)}{\nu}_\mu$ disappearance	$\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e$ appearance	$\overset{(-)}{\nu}_e$ disappearance
CDHS	MiniBooNE ν	Bugey
CCFR84	MiniBooNE $\bar{\nu}$	KARMEN/LSND (xsec)
SuperK/K2K (atm)	LSND	Gallium
MiniBooNE (dis)	KARMEN	
MINOS CC	NOMAD	
	NuMI-MB	

[Conrad, Ignarra, GK, Shaevitz, Spitz, arXiv:1207.4765, accepted by Advances in HEP; see also:
GK et al, Phys.Rev. D80 (2009) 073001,
GK et al, Phys.Rev. D75 (2007) 013011]

Other experimental constraints





$\overset{(-)}{\nu}_\mu$ disappearance

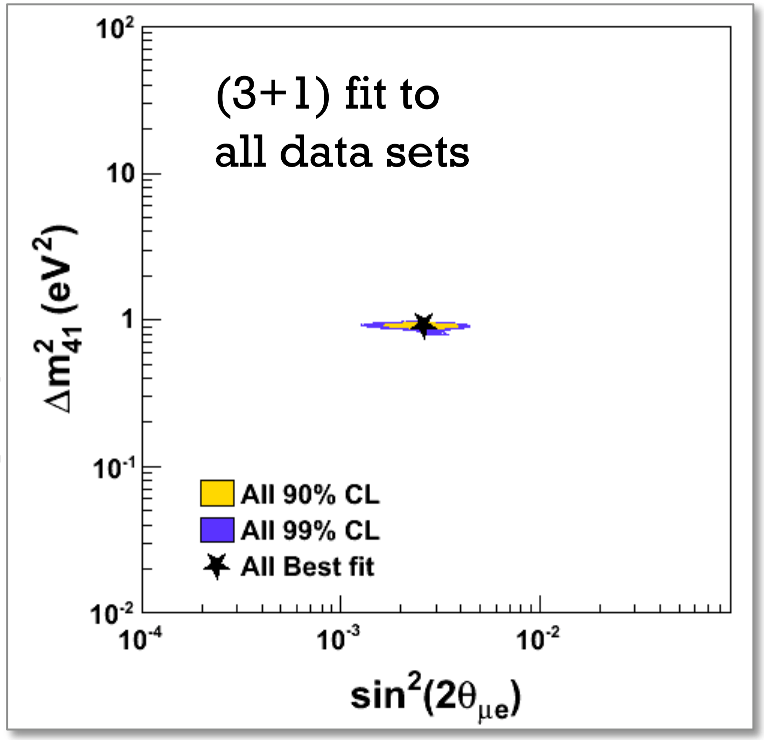
- CDHS
- CCFR84
- SuperK/K2K (atm)
- MiniBooNE (dis)
- MINOS CC

[arXiv:1207.4765]

(3+1) Global Fits to Sterile Neutrino Oscillations

3+1	Δm^2_{41}	$\lvert U_{\mu 4}\rvert$	$\lvert U_{e4}\rvert$
All	0.92	0.17	0.15

[Conrad, Igmarra, GK, Shaevitz, Spitz, arXiv:1207.4765, accepted by Advances in HEP]



Compatibility among data sets included in the fit

Null χ^2 (dof)	Null gof	Best fit χ^2 (dof)	Best fit gof	PG χ^2 (dof)	**PG**
286.5 (240)	**2.1%**	233.9 (237)	**55%**	54 (24)	**0.043%**

Compatibility (PG) Test

A measure of **how well the parameter regions** preferred by different subsets of data **overlap**

$$\chi^2_{PG} = \chi^2_{min,all} - \sum \chi^2_{min,i}$$

$$compatibility,\ PG = prob(\chi^2_{PG}\ ,\ ndf_{PG})$$

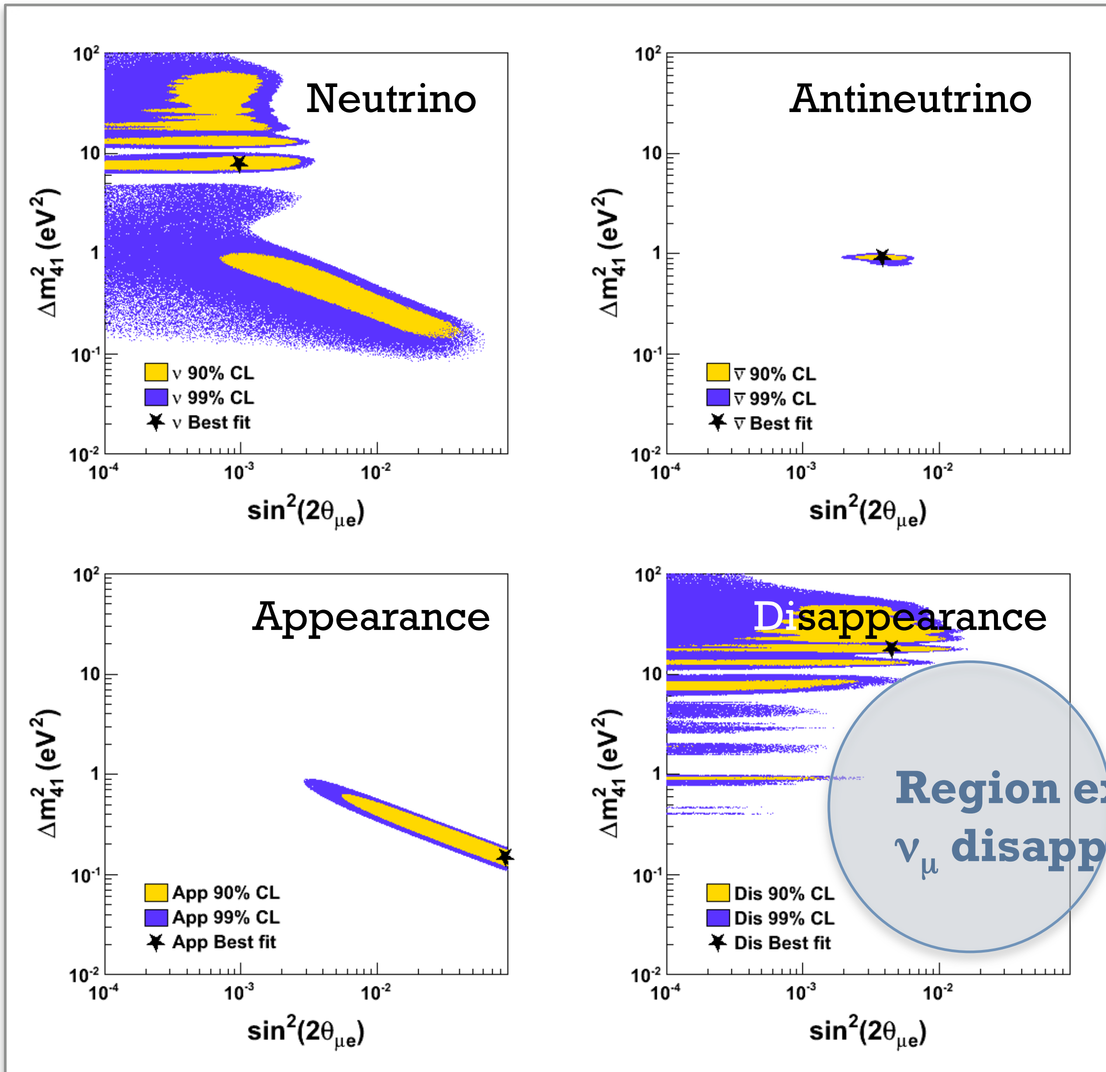
Unlike a χ^2 test, the PG test avoids the problem that a possible disagreement between data sets becomes diluted by data points which are insensitive to the fit.

A commonly used metric.

"Testing the statistical compatibility of independent data sets"
Maltoni & Schwetz, Phys. Rev. D68 (2003) 033020

(3+1) is not enough!

Incompatibilities!



Compatibility $(\nu,\bar{\nu}) = 0.14\%$

Compatibility (app,dis) = 0.013%

Region excluded from ν_μ disappearance experiments

[Conrad, Ignarra, GK, Shaevitz, Spitz, arXiv:1207.4765, accepted by Advances in HEP]

Global Fits: Caveats and Limitations

- Appearance searches assume no disappearance
  - This is an incorrect assumption, given best fit parameters extracted in global fits
  - This may resolve some tension seen in the MiniBooNE appearance data sets, if one allows for ν_e background disappearance

- Need a more advanced statistical and systematic treatment of data sets
  - Compatibility measure needs to be verified with fake data and frequentist studies
  - Need better treatment of systematic correlations between data sets.

    This is a challenging step, but necessary for meaningful quantitative statements on these models

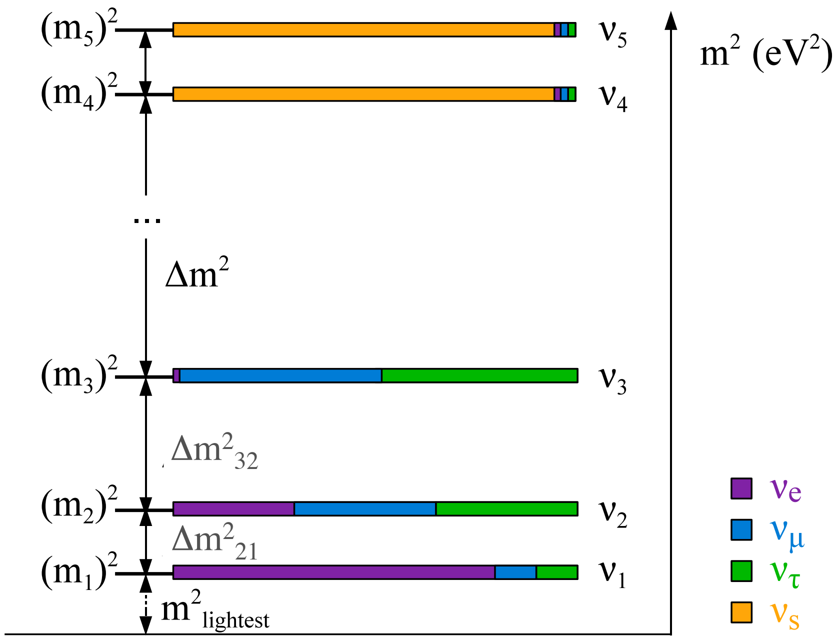
(3+1) is not enough!

Theoretical developments attempting to address inconsistencies:

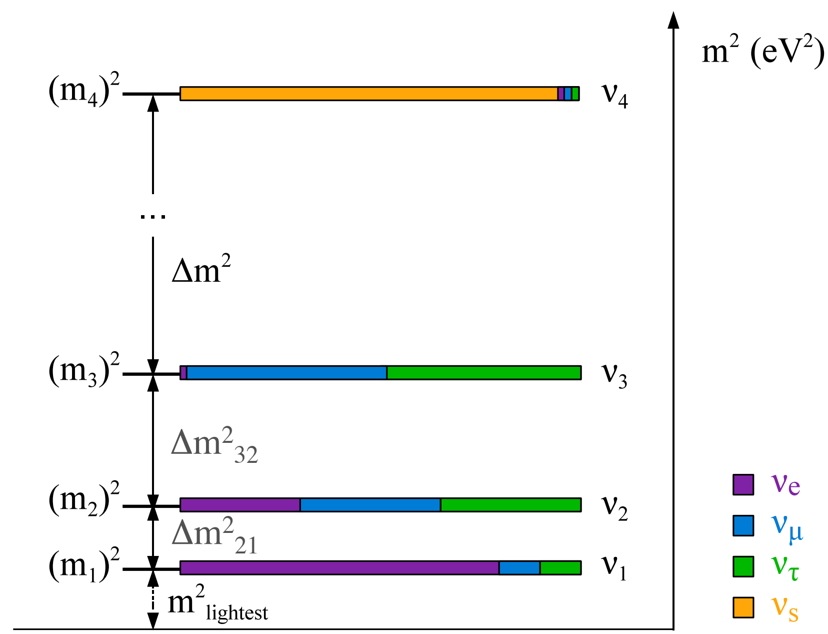
- Fact #1: ν vs $\bar{\nu}$ differences
  Extended sterile neutrino models with CP violation?
- Fact #2: appearance vs disappearance differences
  "Non-standard" oscillations?

Extended models: (1) CP violation

Can have more than one new state…



(3+2)



(3+1)

Extended models: (1) CP violation

Disappearance:

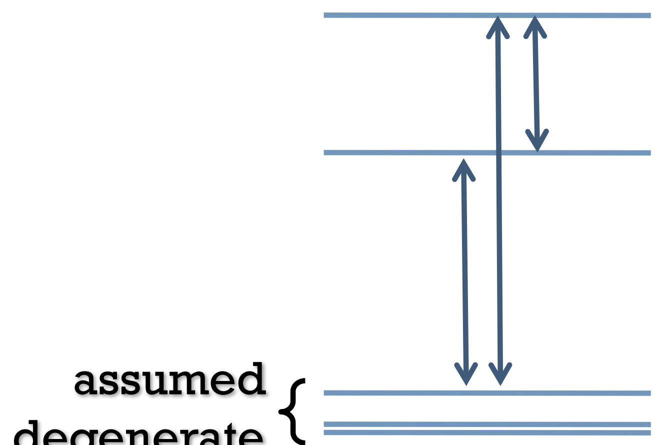
$$P(\nu_\alpha \to \nu_\alpha) = 1 - 4[(1 - |U_{\alpha 4}|^2 - |U_{\alpha 5}|^2) \cdot (|U_{\alpha 4}|^2 \sin^2 x_{41} + |U_{\alpha 5}|^2 \sin^2 x_{51}) + |U_{\alpha 4}|^2 |U_{\alpha 5}|^2 \sin^2 x_{54}]$$

Appearance:

$$P(\nu_\alpha \to \nu_{\beta \neq \alpha}) = 4|U_{\alpha 4}|^2 |U_{\beta 4}|^2 \sin^2 x_{41} + 4|U_{\alpha 5}|^2 |U_{\beta 5}|^2 \sin^2 x_{51} + 8|U_{\alpha 5}||U_{\beta 5}||U_{\alpha 4}||U_{\beta 4}| \sin x_{41} \sin x_{51} \cos(x_{54} - \phi_{45})$$

$$x_{ji} \equiv 1.27 \Delta m^2_{ji} L/E$$

CPV phase



→ 2 effective Δm^2

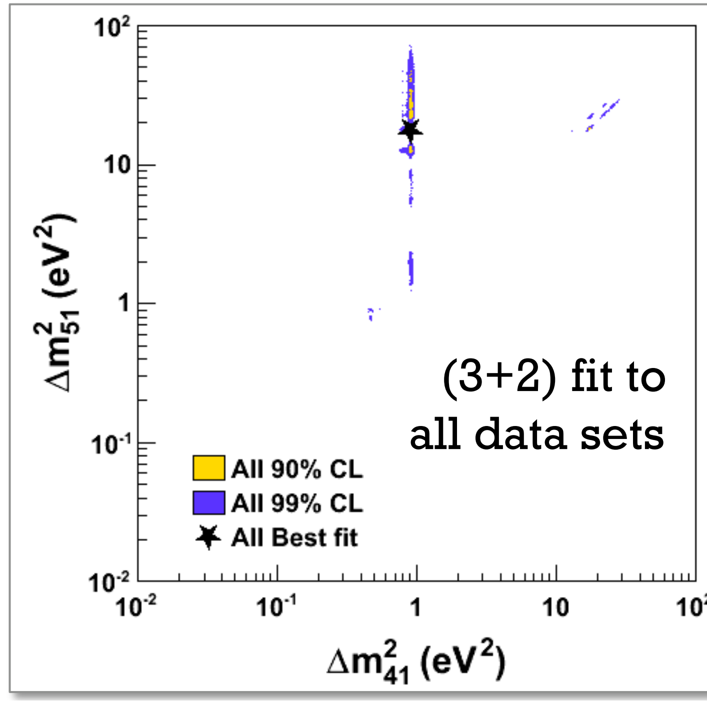
(3+2) is attractive because of **CP violation**

Extended models: (1) CP violation

(3+2): Global Fit

PG ($\nu,\bar{\nu}$) = 5.3%
PG (app,dis)= 0.0082%

Conrad et al, hep-ph/1207.4765



3+2	Δm^2_{41}	Δm^2_{51}	$\lvert U_{\mu 4}\rvert$	$\lvert U_{e4}\rvert$	$\lvert U_{\mu 5}\rvert$	$\lvert U_{e5}\rvert$	ϕ_{54}
All	0.92	17	0.13	0.15	0.16	0.069	1.8π

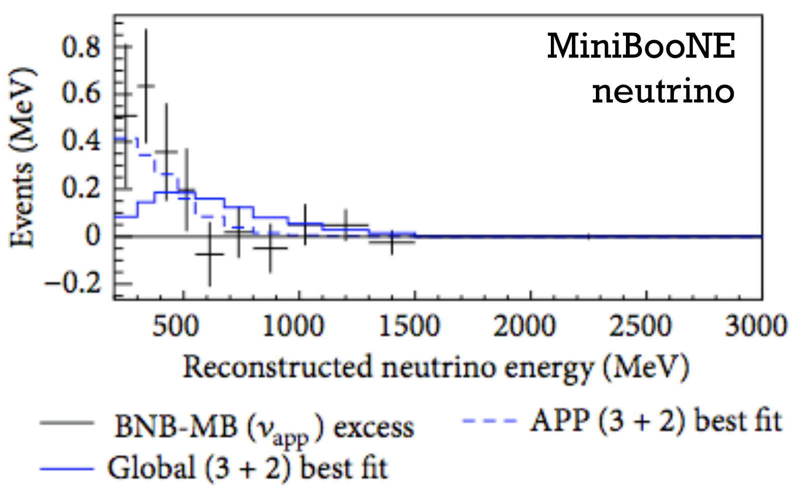
Compatibility among
data sets included in the fit

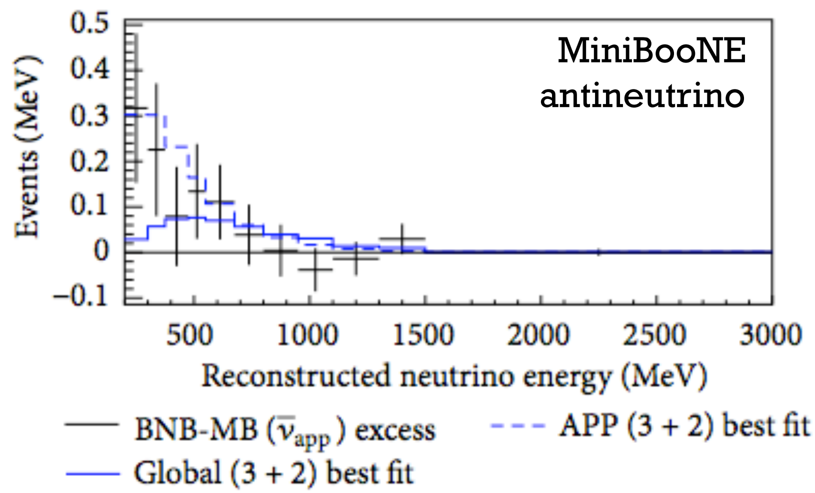
Null χ^2 (dof)	Null gof	Best fit χ^2 (dof)	Best fit gof	PG χ^2 (dof)	**PG**
286.5 (240)	**2.1%**	221.5 (233)	**69%**	63.8 (52)	**13%**

Extended models: (1) CP violation

[Conrad, Ignarra, GK, Shaevitz, Spitz, arXiv:1207.4765, accepted by Advances in HEP]

(3+2) global best fit





(3+2) with CP violation cannot explain MiniBooNE low E excess, unless we throw out disappearance constraints!

More sterile neutrinos? (3+3): Incompatibilities

	χ^2_{min} (dof)	χ^2_{null} (dof)	P_{best}	P_{null}	χ^2_{PG} (dof)	PG (%)
3+3						
All	218.2 (228)	286.5 (240)	67%	2.1%	68.9 (85)	90%
App	70.8 (81)	147.3 (90)	78%	0.013%	17.6 (45)	100%
Dis	120.3 (141)	139.3 (150)	90%	72%	24.1 (34)	90%
ν	116.7 (111)	133.4 (123)	34%	25%	39.5 (46)	74%
$\overline{\nu}$	90.6 (105)	153 (117)	84%	1.4%	18.5 (27)	89%
App vs. Dis	-	-	-	-	28.3 (6)	0.0081%
ν vs. $\overline{\nu}$	-	-	-	-	110.9 (12)	53%

Conrad et al, hep-ph/1207.4765

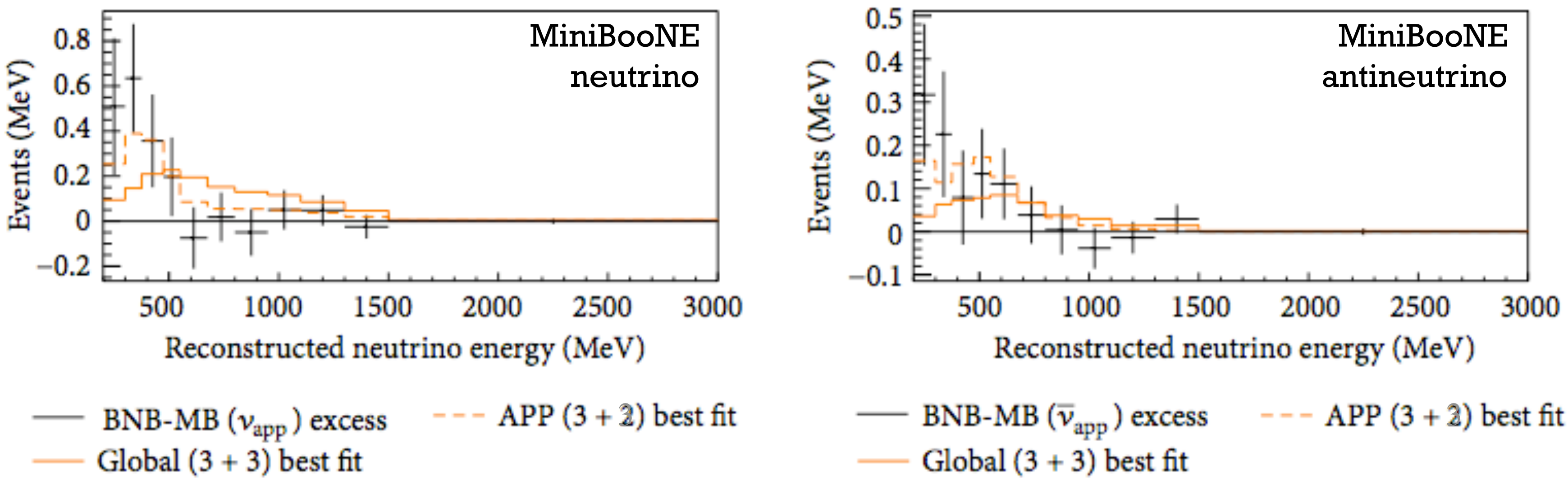
Appearance and disappearance data sets are incompatible under a (3+3) scenario.

PG(app,dis) with MiniBooNE removed from fits: 3.5%

More sterile neutrinos? (3+3): Incompatibilities

[Conrad, Ignarra, GK, Shaevitz, Spitz, arXiv:1207.4765, accepted by Advances in HEP]

(3+3) global best fit



MiniBooNE low energy excess is hard to reconcile within the global picture!

Theoretical developments attempting to address inconsistencies:

Does not explain MiniBooNE low E excess

- Fact #1: ν vs $\bar{\nu}$ ~~differences~~
  ~~Extended sterile neutrino models with~~ CP violation?
- Fact #2: appearance vs disappearance differences
  "Non-standard" oscillations?

Extended models:
(2) Non-standard matter-like effects?

Consider a (3+1) model where:

ν_s experience matter-like potential: $V_s = +A_s$
$\bar{\nu}_s$ experience matter-like potential: $V_s = -A_s$

Effective matter potential in neutrino flavor space:

$$V = \begin{pmatrix} V_{CC}+V_{NC} & 0 & 0 & 0 \\ 0 & V_{NC} & 0 & 0 \\ 0 & 0 & V_{NC} & 0 \\ 0 & 0 & 0 & V_s \end{pmatrix} \simeq \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & V_s \end{pmatrix}$$

V_s-dominant

Effective hamiltonian in matter:

$$H_m = \frac{1}{2E} U \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & m_4^2 \end{pmatrix} U^\dagger + V$$

m_4-dominant

[GK, Shaevitz, Conrad, arXiv:1202.1024, submitted to PRD]

Extended models:
(2) Non-standard matter-like effects?

Consider a (3+1) model where:

ν_s experience matter-like potential: $V_s = +A_s$
$\bar{\nu}_s$ experience matter-like potential: $V_s = -A_s$

General oscillation probability:

$$P(\nu_\mu \to \nu_e) = 4|U_{e4}^M|^2|U_{\mu 4}^M|^2 \sin^2(1.27\Delta m_M^2 L/E)$$

$$\sin^2 2\theta_M = 4|U_{e4}^M|^2|U_{\mu 4}^M|^2$$

Gives effective mixing parameters in matter:

(as functions of Δm^2, $|U_{e4}|$, $|U_{\mu 4}|$, V_s and E)

$$\Delta m_M^2 = \Delta m^2 + 2EV_s$$

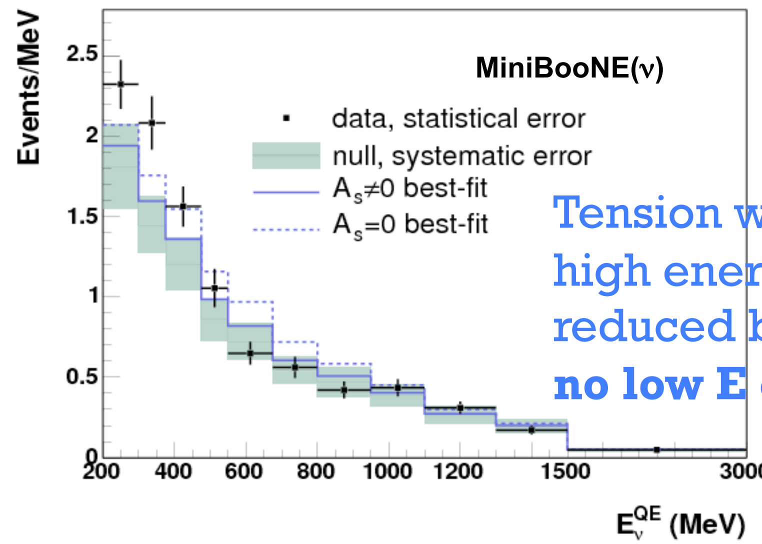
$$\sin^2 2\theta_M = \frac{16(\Delta m^2)^4|U_{e4}|^2|U_{\mu 4}|^2|U_{s4}|^4}{((\Delta m^2 - 2EV_s)^2 + 4(2EV_s\Delta m^2|U_{s4}|^2))(2EV_s - \Delta m^2(1-2|U_{s4}|^2) + \sqrt{(\Delta m^2 - 2EV_s)^2 + 4(2EV_s\Delta m^2|U_{s4}|^2)})^2}$$

Both E- and $\bar{\nu}/\nu$-dependent!

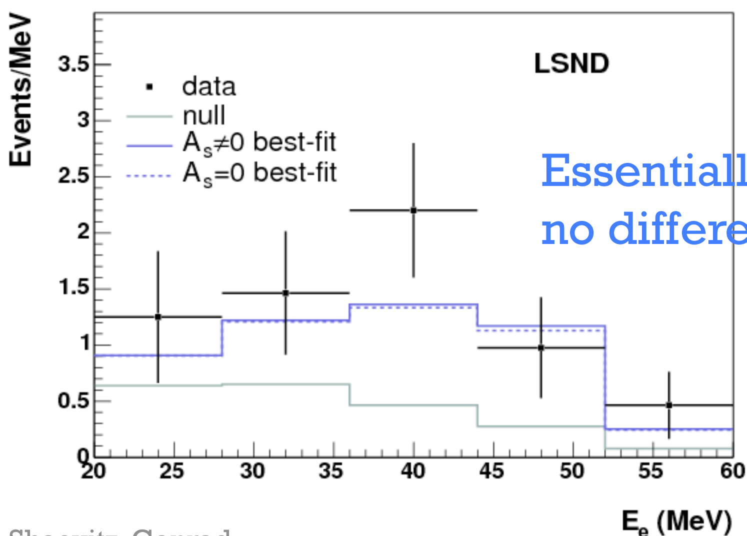
[GK, Shaevitz, Conrad,
arXiv:1202.1024, submitted to PRD]

Extended models:
(2) Non-standard matter-like effects?

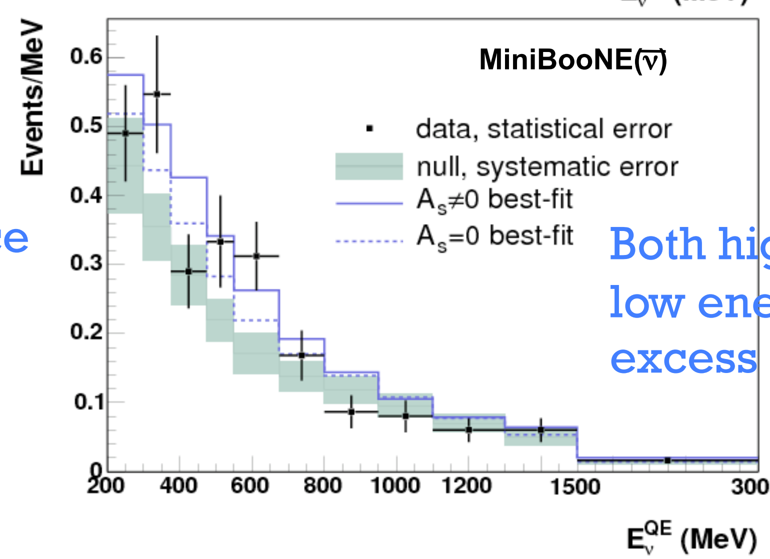
Compatibility increases from 2.3% (A_s=0) to 17.4%, but…



Tension with high energy reduced but **no low E excess**



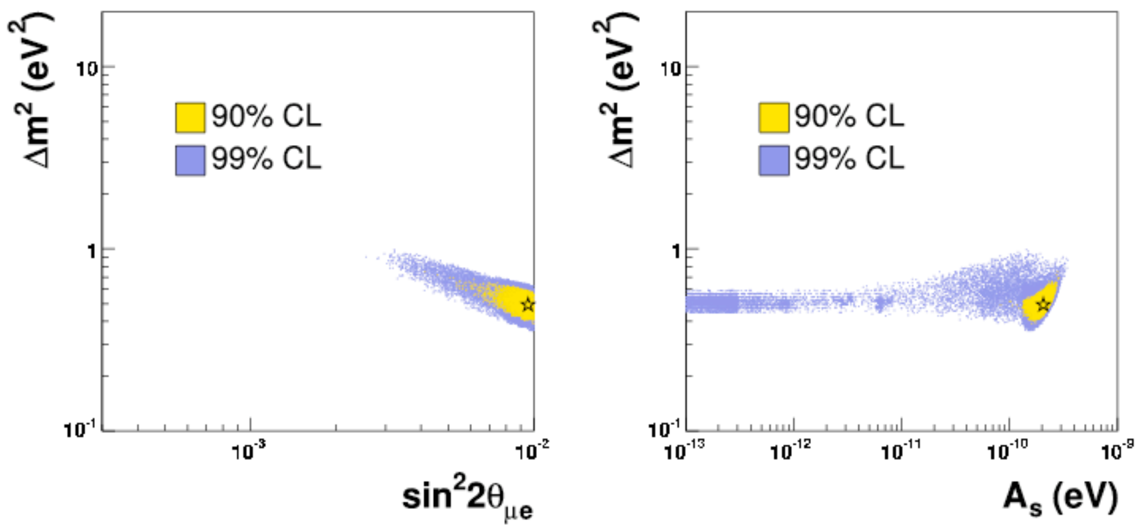
Essentially no difference



Both high and low energy excess

[GK, Shaevitz, Conrad, arXiv:1202.1024, submitted to PRD]

Extended models:
(2) Non-standard matter-like effects?



Fit prefers a large $A_s \sim 2.0\times10^{-10}$ eV

Best-fit vacuum oscillation parameters:

$\Delta m^2 = 0.47\ \mathrm{eV}^2, \quad \sin^2 2\theta = 0.01$

(Note: for standard matter effects, $A_e = \sqrt{2} G_F n_e \sim 10^{-13}$ eV)

[GK, Shaevitz, Conrad,
arXiv:1202.1024, submitted to PRD]

Theoretical developments attempting to address inconsistencies:

Does not explain MiniBooNE low E excess

- ~~Fact #1: ν vs $\bar{\nu}$ differences~~
  ~~Extended sterile neutrino models with CP violation?~~
- ~~Fact #2: appearance vs disappearance differences~~
  ~~"Non-standard" oscillations?~~

MiniBooNE low E excess?? difficult to interpret...

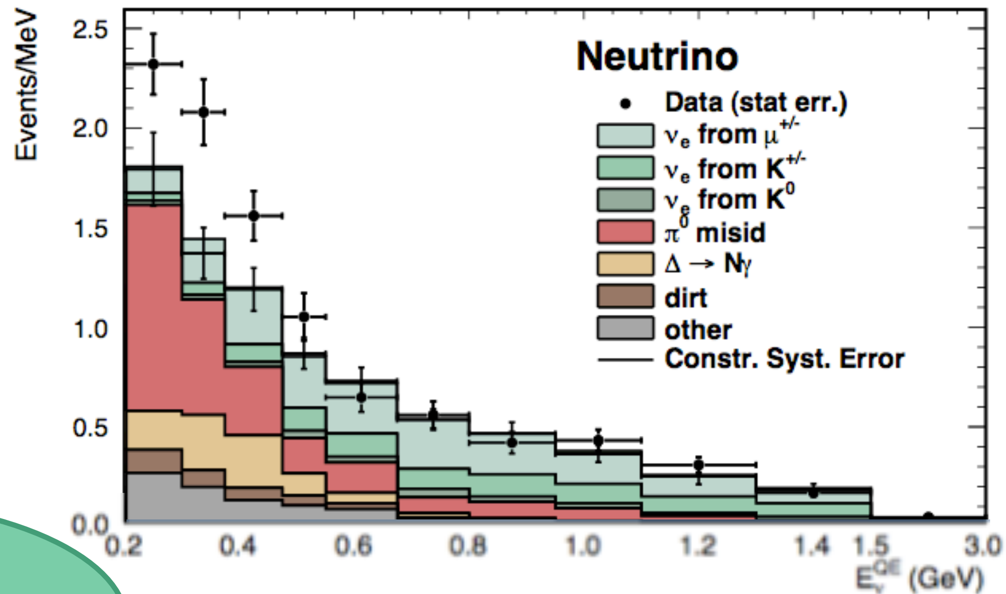
Other theoretical interpretations:

- CPT violation
- Heavy (sterile) neutrino decay
- Extra dimensions
- New interactions
- Altered neutrino dispersion relations

None of these provide an "elegant" solution…

Puzzle piece #2: MiniBooNE

Low E excess: Are we missing something?



Unaccounted ν_e / ν_μ disappearance?

Energy reconstruction? Cross-section/ nuclear effects?

Electron-like misestimated or new background?

Single-photon mis-estimated or new background?

Outline

1. Evidence for and shortcomings of (light) sterile neutrino oscillations

Experimental hints for "short baseline" neutrino oscillations
$\nu_\mu \rightarrow \nu_e$ and $\nu_e \rightarrow \nu_{\cancel{e}}$

Lack of signals in $\nu_\mu \rightarrow \nu_{\cancel{\mu}}$,
Simplest models are insufficient

Cosmological constraints

2. Future phenomenological tests of sterile neutrino models

Limits from cosmology

Neutrino energy density in radiation dominated era

$$\rho_\nu = N_{eff} \frac{7\pi^2}{120} T_\nu^4$$

from CMB

Affects expansion rate at that time: $H^2(t) \simeq \frac{8\pi G}{3}(\rho_\gamma + \rho_\nu)$

Primordial element abundance:

Electron neutrinos determine p/n ratio

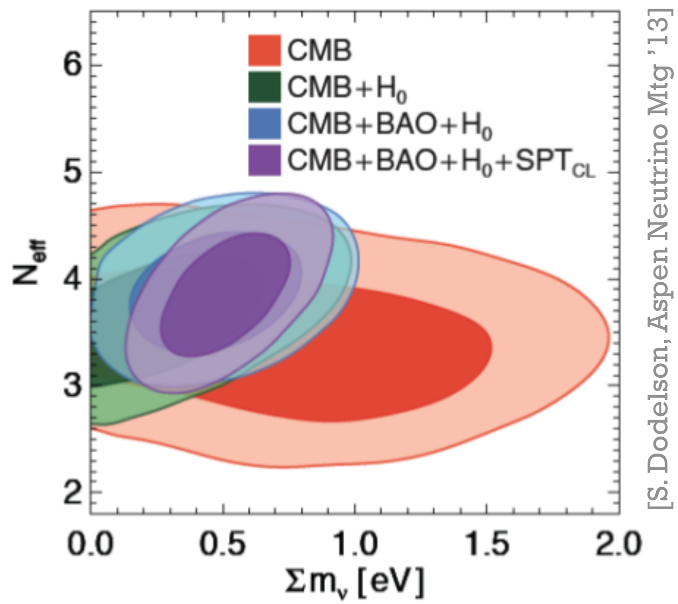
$$\nu_e + n \leftrightarrow p + e^-$$
$$\bar{\nu}_e + p \leftrightarrow n + e^+$$

All neutrinos influence expansion rate and can alter light element abundance (mostly ^{4}He)

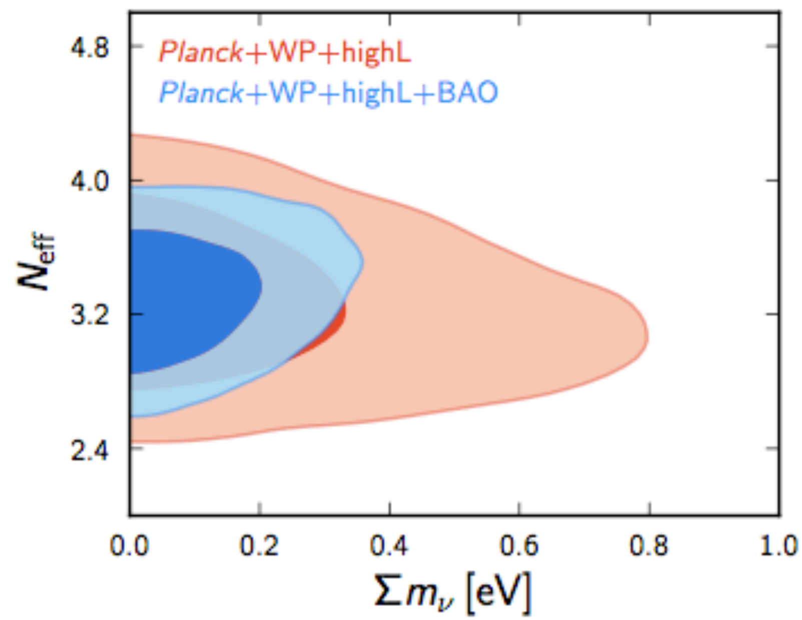
CMB anisotropies and Large Scale Structure:

Insensitive to flavor content; sensitive to neutrino stress energy tensor
→ N_{eff} and m_i

Limits from cosmology

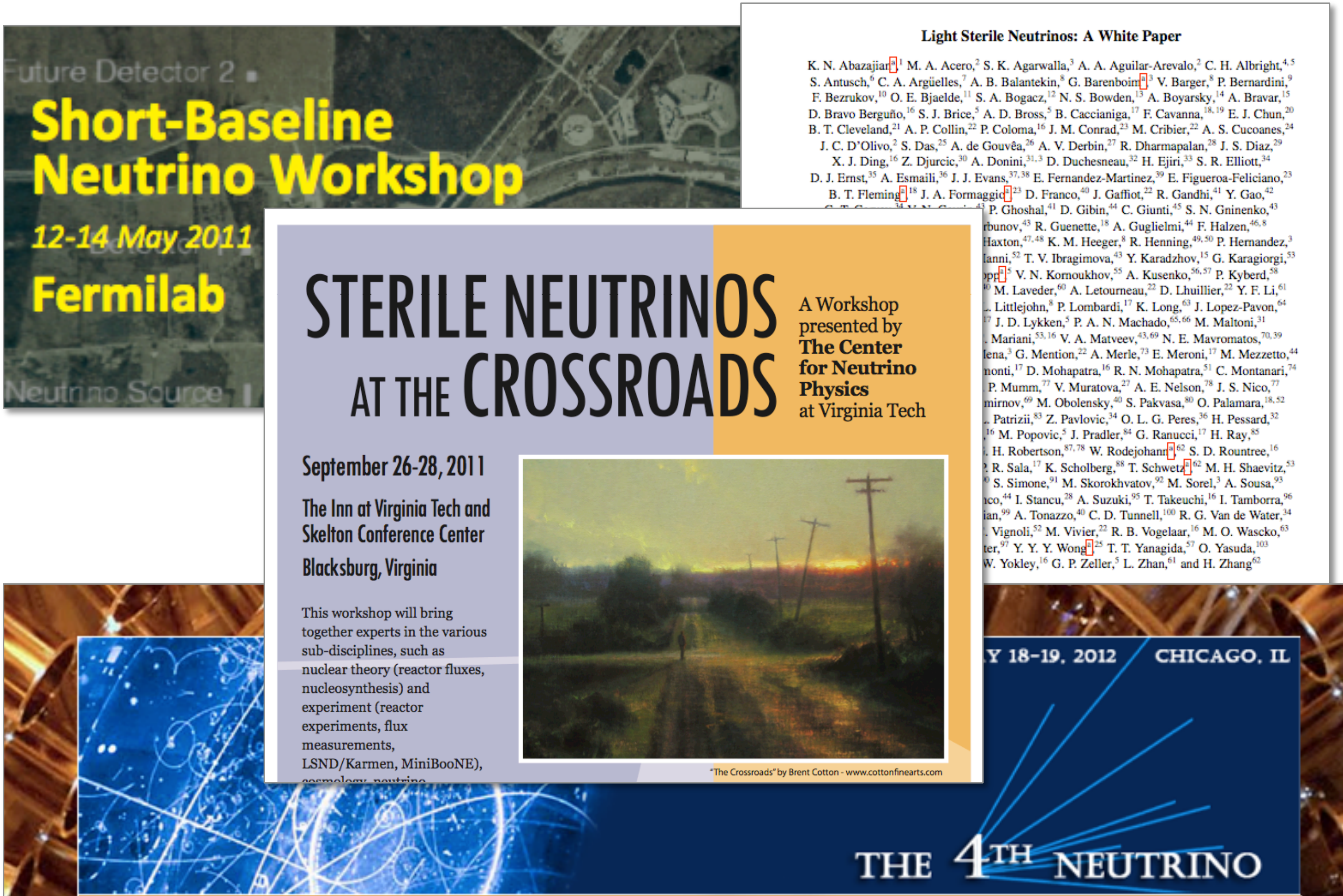


arXiv:1303.5076



(1) N_{eff} somewhat compatible with additional degrees of freedom.
(2) Limits on m_s assuming sterile neutrinos are fully thermalized are incompatible with global fits (m_s >1-2 eV strongly disfavored).
Limits can be evaded with further modifications to the ΛCDM model.

Currently a puzzle in neutrino physics!



What do we need to address the question of sterile neutrinos?

(a) New physics models
(b) Better statistical treatment of global fits
(c) New, definitive experimental tests
(d) All of the above

Outline

1. **Evidence for and shortcomings of (light) sterile neutrino oscillations**

Experimental hints for "short baseline" neutrino oscillations
$\nu_\mu \rightarrow \nu_e$ **and** $\nu_e \rightarrow \nu_{\cancel{e}}$

Lack of signals in $\nu_\mu \rightarrow \nu_{\cancel{\mu}}$ **,**
Simplest models are insufficient

Cosmological constraints

2. **Future phenomenological tests of sterile neutrino models**

Accelerator-based experiments:

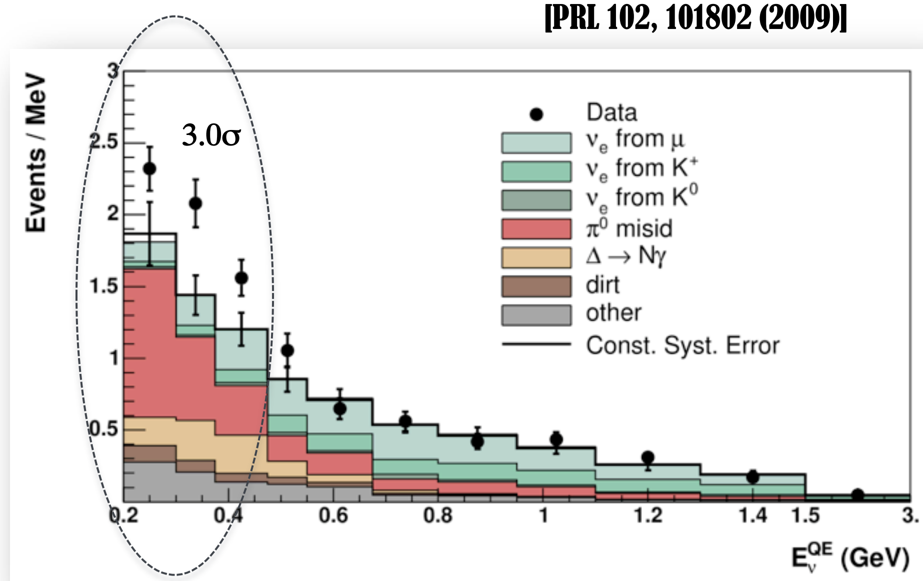
- MINOS+ (funded)
- MiniBooNE+ (proposal)
- MicroBooNE (funded)
- LAr1 (proposal in preparation)
- NESSiE (proposed)
- νSTORM (LOI)

ν_μ or ν_e beams, can search for ν_μ or ν_e disappearance and/or $\nu_\mu \rightarrow \nu_e$, $\nu_e \rightarrow \nu_\mu$ appearance

MicroBooNE

- Primary physics goal: Investigate the nature of the MiniBooNE low energy excess
- Is the excess due to e or γ?

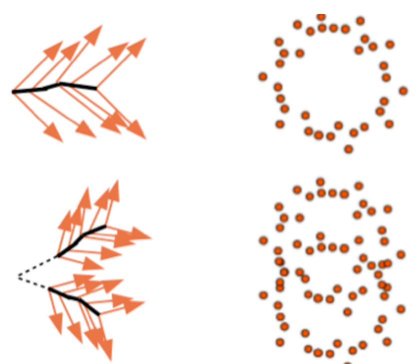
MiniBooNE unexplained "low energy excess"
[PRL 102, 101802 (2009)]



Single e and single γ are indistinguishable in a cherenkov detector…

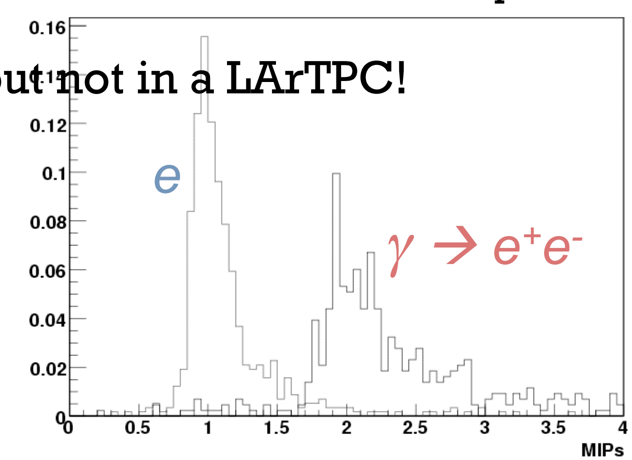
electron:
short track,
multiple scattering,
bremsstrahlung

photon(s):
photoconversion
→ electron-like track(s)



Energy loss in first 24mm of track:
250 MeV electron vs. 250 MeV photon

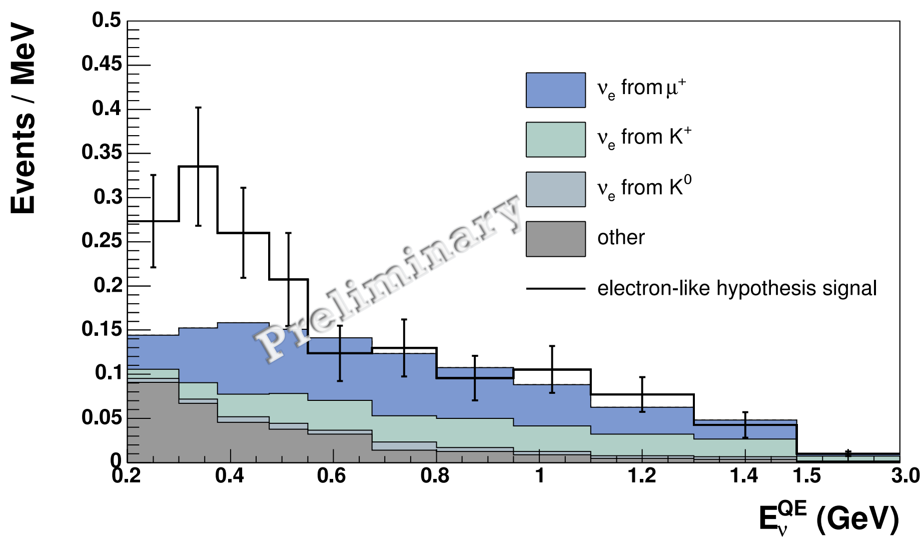
…but not in a LArTPC!



MicroBooNE

"Low E excess":

What MicroBooNE expects to see if excess is due to single e



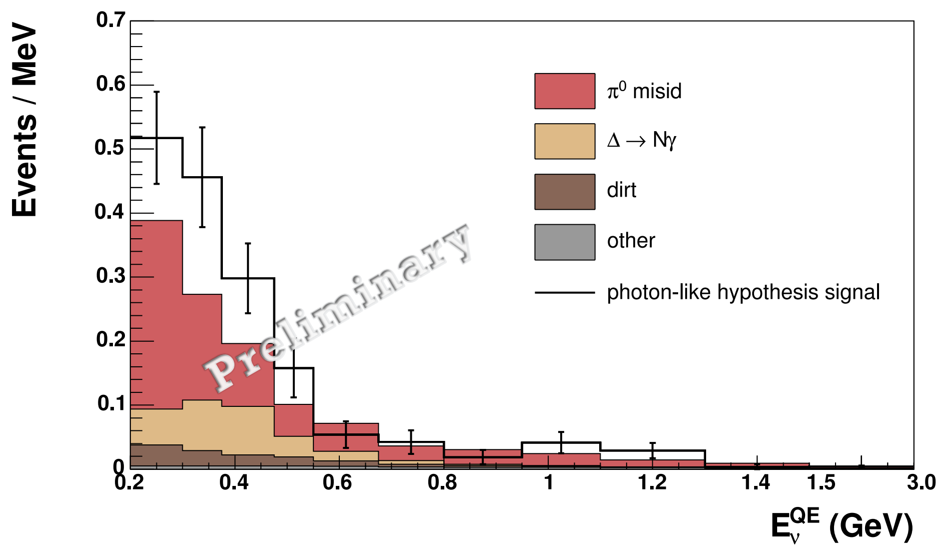
Possible explanation:
$\nu_\mu \rightarrow \nu_e$ nonstandard oscillations
(sterile neutrinos, extra dimensions, NSI,…)

About **37 excess events** above a background of 45 events
→ **5.7σ statistical** significance

MicroBooNE

"Low E excess":

What MicroBooNE expects to see if excess is due to single γ



Possible explanation: background γ or π^0 or "new" single photon production

e.g.

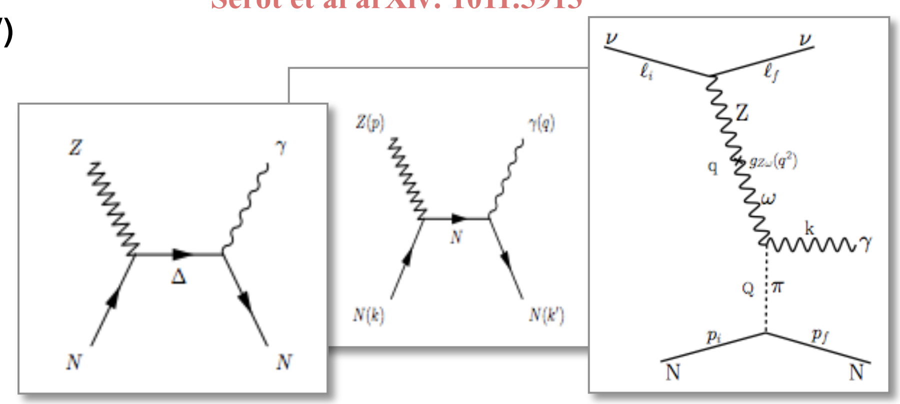
R. Hill arXiv: 0905.0291

Jenkins et al arXiv:0906.0984

Serot et al arXiv: 1011.5913

About **37 excess events** above a background of 79 events

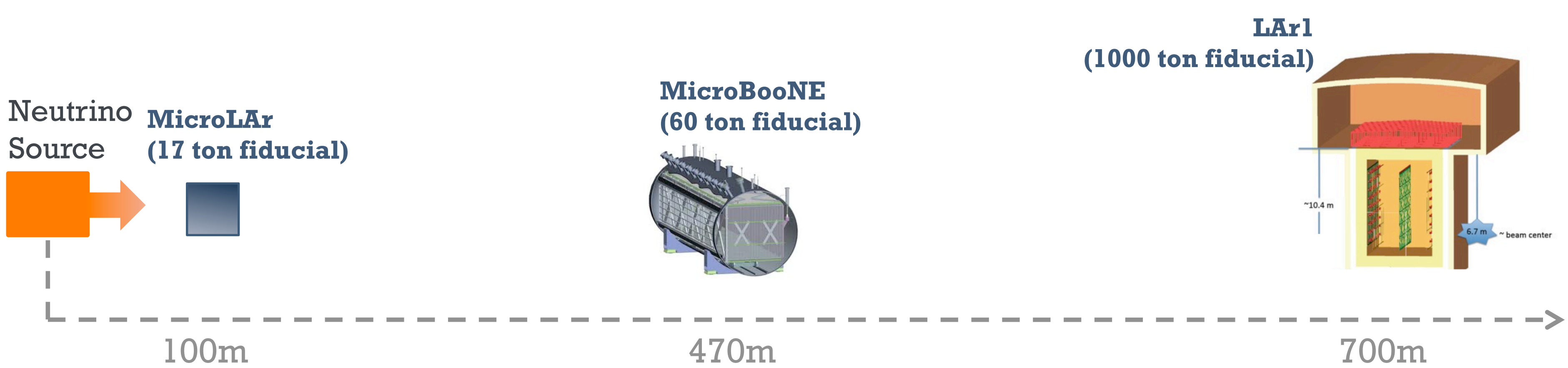
→ **4.1σ statistical** significance



LAr1

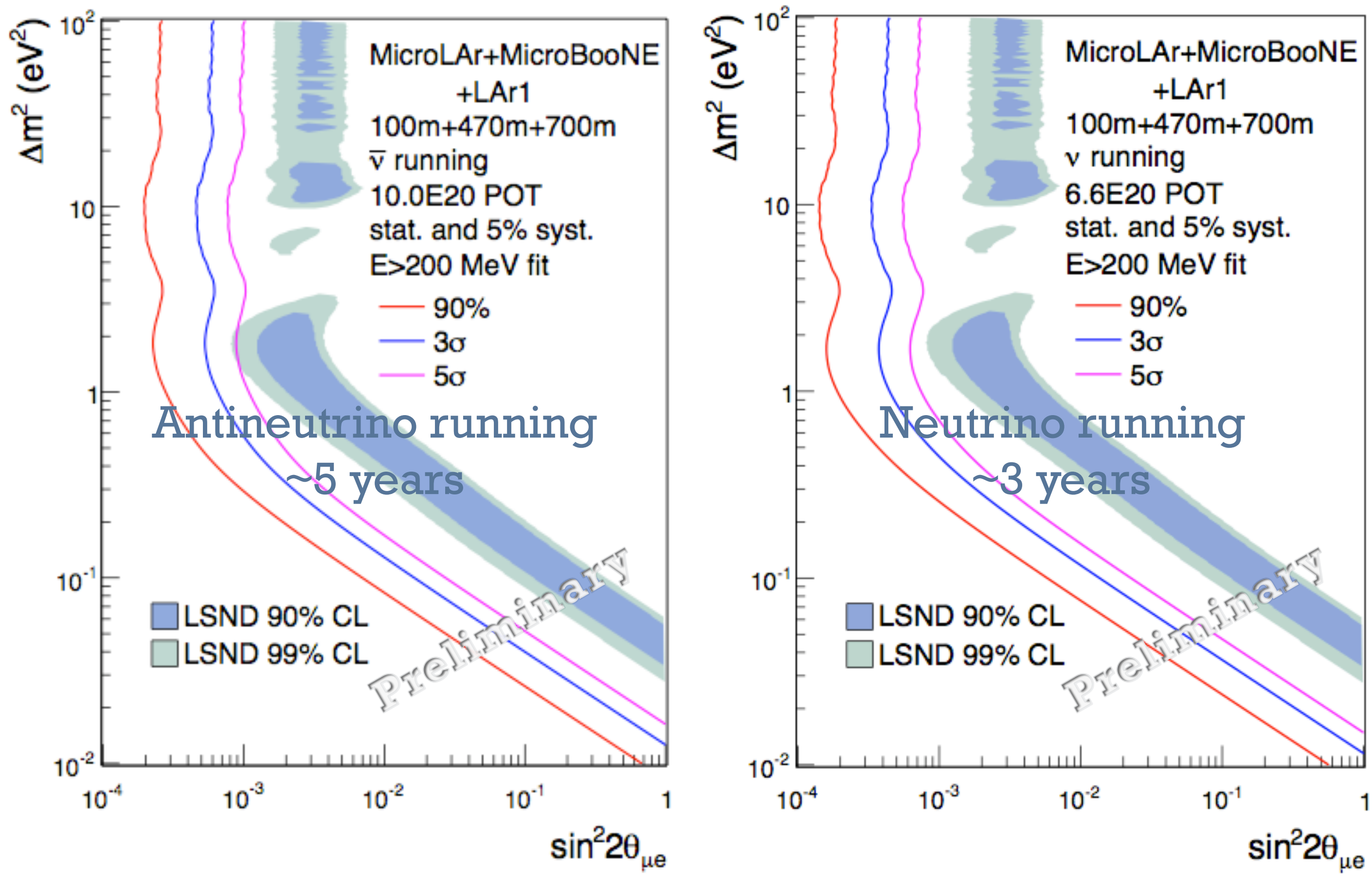
- A second and third LArTPC placed in the Booster Neutrino Beam at Fermilab, in line with MicroBooNE
- Near/far comparison for short-baseline oscillation search
- **Definitive test of MiniBooNE/LSND anomalies**

LAr1: can serve as a small-scale prototype for LBNE



LAr1

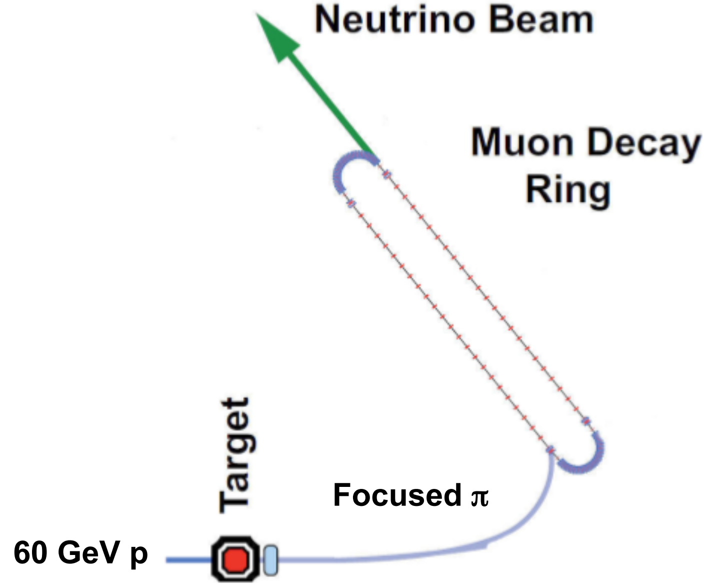
- Physics reach: Definitive (5σ) test of LSND and MiniBooNE in both neutrino and antineutrino modes



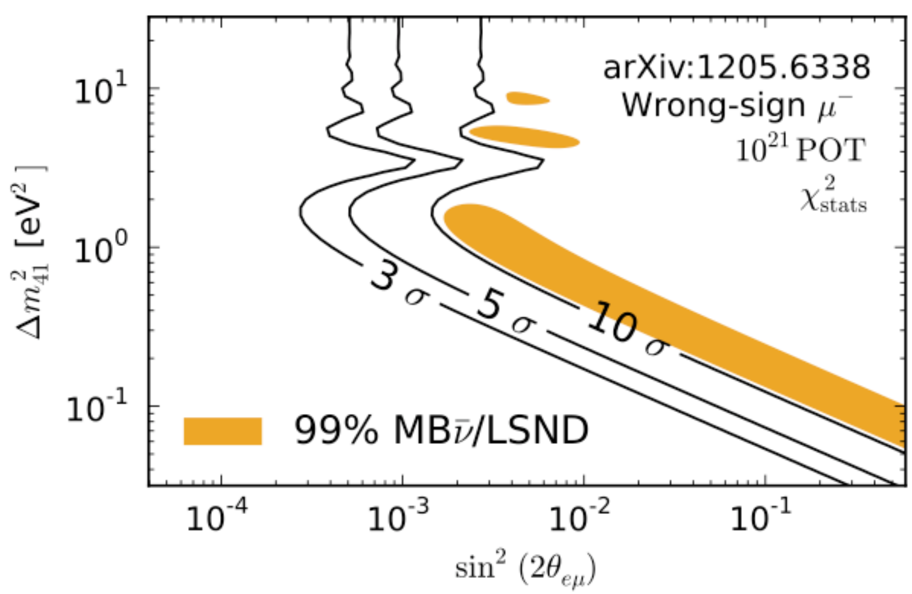
- Also $\overset{(-)}{\nu}_e$ and $\overset{(-)}{\nu}_\mu$ disappearance

NuSTORM

- Neutrinos from STORed Muons
- ν_e flux from $\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$
- $\nu_e \rightarrow \nu_\mu$ appearance
- 3.8 GeV/c muons and 1.3kton sign-selecting (MINOS-style) detector at 2km →
  10 sigma sensitivity
  to MiniBooNE/LSND !
- Also, ν_e disappearance



arXiv:1206.0294



Decay-At-Rest experiments:

- OscSNS
- Super-K
- K-DAR

ν_μ and ν_e isotropic fluxes,
can search for $\nu_\mu \rightarrow \nu_e$ appearance,
and ν_e disappearance, ν_μ disappearance

Reactor-based experiments:

- SCRAAM
- Nucifer
- Stereo

Radioactive source experiments:

- Borexino, Ce-LAND, Daya Bay
- Borexino, SNO+Cr
- RICOCHET
- IsoDAR

Lower E ν_e isotropic flux, can search for ν_e disappearance

IsoDAR

- New idea: High intensity nuebar source from ^{8}Li β-decay and liquid scintillator/water detector (e.g. Kamland)
- ^{8}Li produced by high-intensity proton beam from 60MeV cyclotron

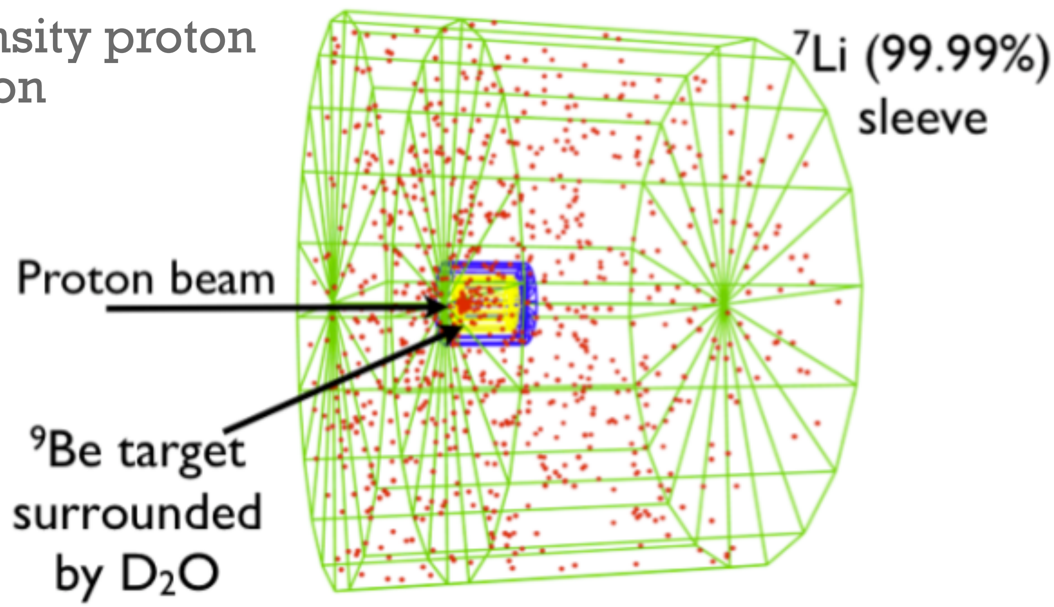
$p\ (60\ \mathrm{MeV}) + {}^{9}\mathrm{Be} \rightarrow {}^{8}\mathrm{Li} + 2p$

- plus many neutrons since low binding energy

$n + {}^{7}\mathrm{Li}\ (\mathrm{shielding}) \rightarrow {}^{8}\mathrm{Li}$

${}^{8}\mathrm{Li} \rightarrow {}^{8}\mathrm{Be} + e^{-} + \bar{\nu}_e$

- Mean $\bar{\nu}_e$ energy = 6.5 MeV
- $2.6\times10^{22}\ \bar{\nu}_e$ / yr

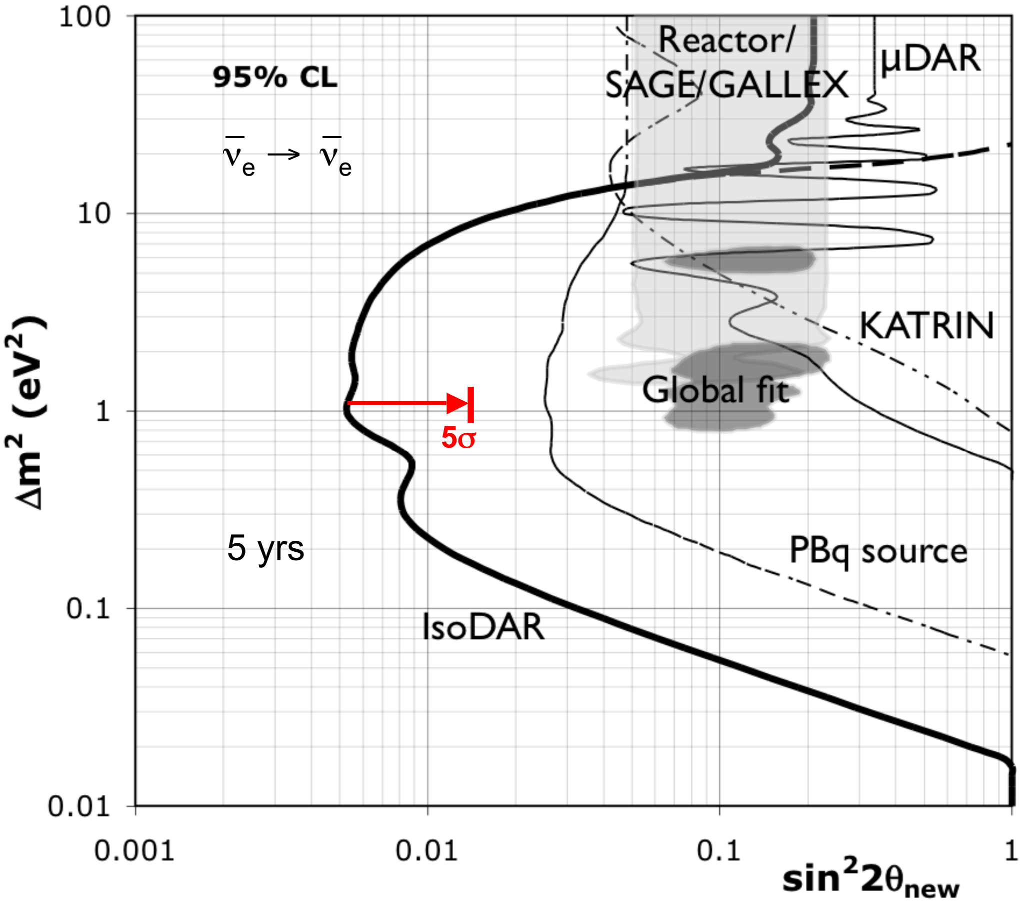


- Nuebar disappearance and oscillatory behavior vs L/E
- **Definitive test of reactor anomaly**

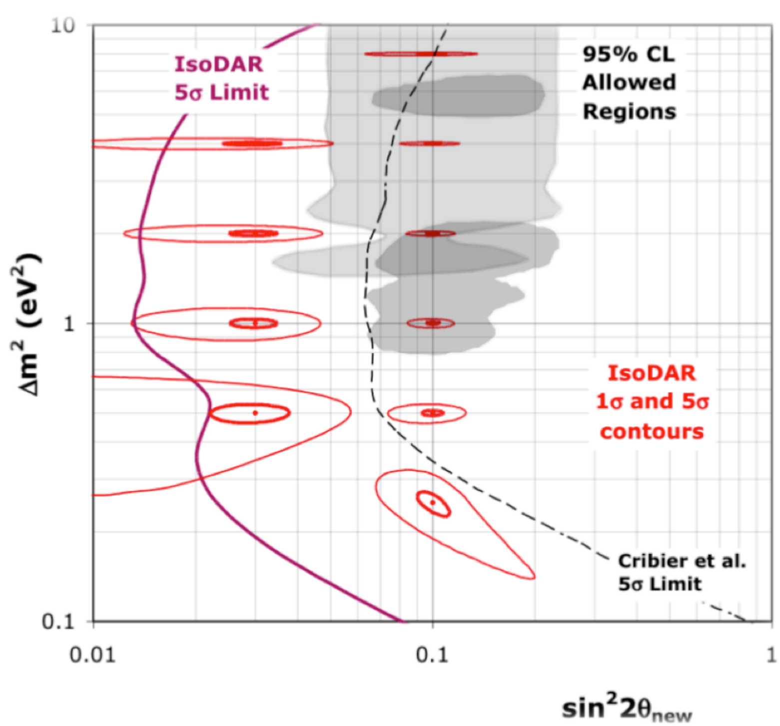
Phys Rev Lett 109 141802 (2012) arXiv:1205.4419

IsoDAR

IsoDAR $\bar{\nu}_e$ disappearance oscillation sensitivity (3+1):

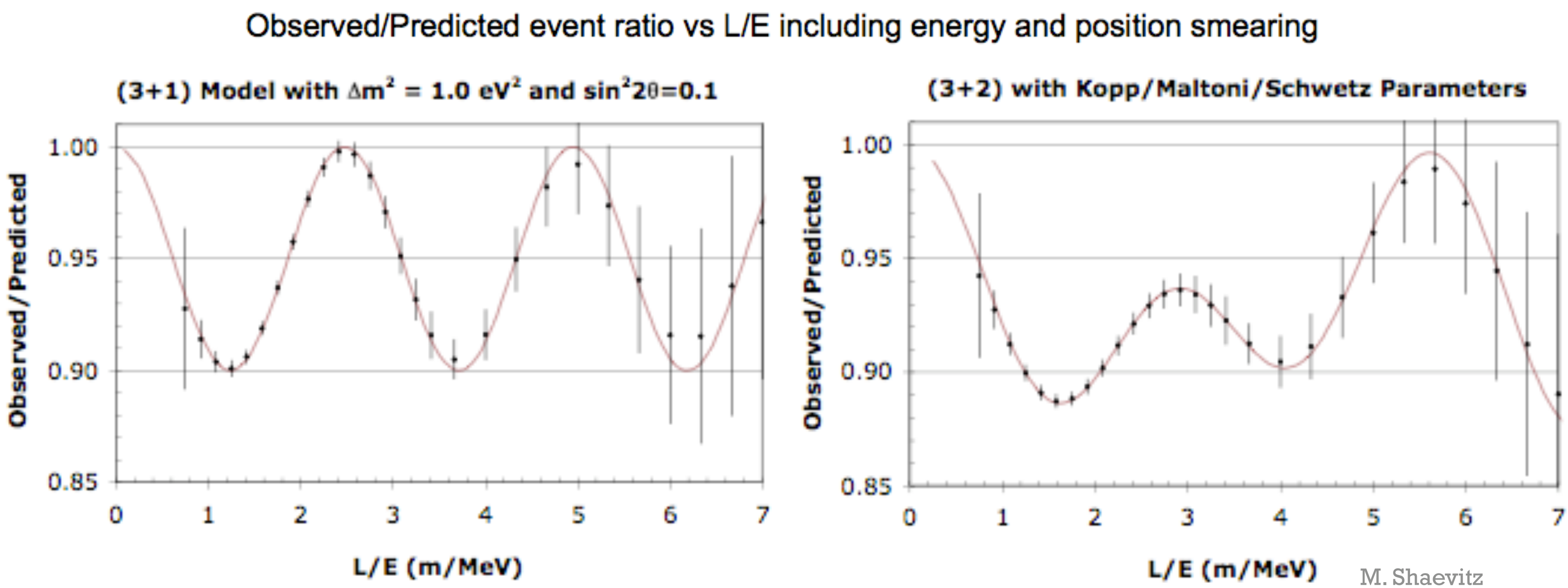


M. Shaevitz



5σ (discovery) sensitivity to parameters
allowed by short-baseline reactor measurements!

IsoDAR



IsoDAR's high statistics and good L/E resolution:
potential for distinguishing between
simple (left) and more complicated (right) sterile neutrino oscillation models.

End remarks

Theoretical motivation for light (~1 eV) sterile neutrinos is perhaps not so strong, though sterile neutrinos with sizable mixing emerge in several models of neutrino mass (heavy sterile neutrinos…).

Their discovery would point towards new physics.

"…their role is relevant enough to justify an open mind attitude and a close look for any, yet tiny, evidence for new effects beyond the *too much* successful Standard Model." [Theorist Anonymous]

Experimental hints may be right in front of us, albeit not completely understood. Need new, definitive experiments. Model-independent searches should be given highest priority.

Thank you!